Mid-term report

20 July - 13 October 2003

Satellite monitoring of the FDEP Gulf dispersal of the Piney Point treated wastewater

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Summary

Operational satellites such as MODIS, SeaWiFS, and AVHRR provide a unique means to monitoring large-scale biological, physical, and chemical state of the ocean. Satellite observations are used as part of the Piney Point monitoring effort. We report our findings here, covering the dispersal conducted over nineteen barge trips. About 122 million gallons (slightly more than half of the mission goal) of treated Piney Point wastewater were discharged over this period. The satellite observations complement other data from field samples, surface float trajectories, and model results. To date, satellite data analyses have provided real-time and accurate information on the position of the Loop Current, the strong oceanic current that would carry materials away from the dispersal region and therefore help minimize any possible coastal impact. The satellite data were instrumental prior to the initiation of the dispersal to outline the area where the barge would operate to disperse the treated wastewater. In addition, without the weekly satellite data analysis it would be impossible to tell which way dispersed waters are likely to move in a synoptic fashion, and therefore whether any dispersed materials would stagnate or re-circulate at the dispersal site.

Our ***primary*** purpose and objective is to document major circulation patterns, changes in ocean color that imply change in water quality, and help determine whether there is any impact of the discharge on our near-shore environment. To address this question, we focused on several areas on the West Florida Shelf (including the downstream area) and near the Florida Keys, and used the highly quality SeaWiFS satellite data to study the long-term (seven years) patterns within each selected area. The baseline ocean color analysis conducted using historical data spanning several years prior to the initiation of dispersal was required to understand whether there have been changes occurring concurrent with the dispersal of Piney Point wastewater. The results show that some areas of the West Florida Shelf showed an abundance of colored dissolved organic matter (CDOM) in August 2003, which is higher by 20-30%, compared to previous months, but that chlorophyll concentration (a biological indicator) in these areas remained virtually unchanged over several months during the discharge period. Chlorophyll concentration in August and September 2003 (initial dispersal started on 20 July) remained within the normal range (on average, below 0.2 mg m^{-3} for all deep water areas and below 0.5-0.6 mg m^{-3} for near shore waters off the central Florida coast). Therefore, we conclude that there was no apparent biological effect (either positive or negative) observed over the selected areas.

We also carefully examined the daily imagery, particularly those concurrent with the discharge, by stretching the color bands and zooming into areas within images. We found that the effects of river waters coming into the dispersal region from the coasts of the northeastern Gulf of Mexico, cloud cover, and algorithm artifacts mask any local effects that the dispersal could have had. In a few cases the dispersal may have contributed to a change in the color of water downstream of the area, but the answer is not conclusive.

We attribute this finding (i.e., no apparent biological effect so far) to several factors, including the persistent presence of river plumes in the region this year, fast dilution of the wastewater by major ocean currents, and the relatively small amounts of nutrients added to the large oceanic system by the discharged water. If the water was to be dispersed in near shore environments or to move inshore and accumulate in stagnant waters, enhanced biological activity would likely result from the discharge and may be detected by the satellites.

As the mission progresses, we will continue our daily monitoring efforts. Updates to our daily imagery and weekly reports can be found online at http://imars.usf.edu/Piney_Point/.

REPORT

Background

To date, satellite data analyses have provided real-time and accurate information on the position of the Loop Current, the strong oceanic current that would carry materials away from the dispersal region and therefore help minimize any possible coastal impact. The satellite data were instrumental prior to the initiation of the dispersal to outline the area where the barge would operate to disperse the treated wastewater. Without the weekly satellite data analysis it would be impossible to tell which way dispersed waters are likely to move in a synoptic fashion, and therefore whether any dispersed materials would stagnate or re-circulate at the dispersal site.

For additional background information, please visit the Florida Department of Environmental Protection (FDEP) online at http://www.dep.state.fl.us/secretary/comm/2003/piney_point.htm.

Satellite Instruments and Color Interpretations

See Appendix A.

FDEP Dispersal Status (as of 13 October 2003)

Nineteen discharges were completed in the period covered by this report, commencing on 20 July, 24 July, 28 July, 1 August, 5 August, 10 August, 13 August, 18 August, 22 August, 27 August, 31 August, 7 September, 11 September, 15 September, 20 September, 24 September, 1 October, 6 October, and 11 October, respectively. A total of approximately 122 million gallons of treated wastewater were released via barge transportation and offshore dispersal.

Satellite Monitoring Results

This document focuses on satellite imagery (remote sensing), and describes only one part of the monitoring efforts being undertaken by several groups. These other monitoring groups focus their efforts on water sample analysis, and will post their results independently.

Our weekly reports can be found at http://imars.usf.edu/Piney_Point/reports/, and daily satellite imagery can be found at http://imars.usf.edu/Piney_Point. Here we summarize our findings to date since the initial dispersal on 20 July 2003.

Pre-dispersal Condition

Figure 1 shows a MODIS chlorophyll composite satellite image for 18-29 July 2003 (composite images are created to help minimize the effects of cloud cover). The image is overlaid with water depth (bathymetry) contours from 30 to 2000 m; outlines of the dispersal area (white box centered at about 27.2°N 85.5°W), and ship survey transect line. Because the initial dispersal started on 20 July, pre-dispersal baseline information can be derived from this image.

Note that in spite of the units provided on the color scale with Figure 1, the yellow-red colors along the coasts do *not* necessarily mean that chlorophyll concentration is higher than 2-5 mg m^{-3} there. Instead, these colors indicate the presence of high content of colored dissolved matter, suspended particles, and possibly some bottom effects. Indeed, these factors lead to false chlorophyll readings and waters associated with these colors, especially those along the beaches, which can be relatively clear waters.

Note also the southward flow of plumes of colored water from the continental shelf of the northeastern Gulf of Mexico. This plume contains Mississippi River water and it extends south in two plumes (indicated in Figure 1 by arrows). One is parallel to West Florida Shelf (WFS), clearly crossing the western half of the proposed dispersal area. The other extended southward over the middle of the shelf. A pre-dispersal cruise survey to collect baseline water quality data in the Gulf prior to dispersion operations (transect line overlaid on Fig. 1) showed that salinity in the two river plumes was as low as 32 – 33 (grams per kg of seawater; Fig. 1 bottom panel). Such low salinities offshore are evidence of river water. In contrast, Gulf waters typically have salinities higher than 35. Episodic rains cannot cause such a large and geographically focused salinity drop. The flow patterns of the river plume are typical of patterns seen during this season in at least the past five years. It is driven mainly by wind and surface heat flux (He and Weisberg, 2002), and by entrainment by major water circulation features (such as the Loop Current and its eddies).

MODIS Imagery Sequence and Large-Scale Features

Figures 2 to 9 show MODIS (Esaias et al., 1998) satellite-derived "chlorophyll" images from mid-July to mid-October. The dominant circulation patterns inferred by changes in the color of waters and by the surface Argo float tracks are overlaid on some images. Six areas of interest (for long-term studies of color changes) are outlined on Fig. 9. Explanation of relevant patterns and phenomena observed is included in the figure captions.

Near the dispersal area, the presence of river plume water from the northeastern Gulf of Mexico (particularly the Mississippi delta and Mobile Bay) has persisted sine late May 2003. The presence of this water is not related to Mississippi river discharge, since the daily discharge volume, as monitored by the USGS river gauges, shows no significant increase as compared with previous years.

Figures 10 and 11 show the mean weekly wind between 14 May and 10 June and between 6 and 30 August, respectively. In response to the Coriolis effect (an artificial force defined to describe the effect of the Earth's rotation on moving objects as viewed by an observer on Earth) the surface current in the northern hemisphere moves up to 45 degrees to the right of the wind direction. During the period covered here, winds in and near the Piney Point dispersal area were most often relatively weak (order of 10 m/s or 19.4 knots or less. Note that wind at any moment can be stronger, as data shown in these figures are the weekly average "net" effects where winds with opposite directions are cancelled), and of varying direction compared to winds farther offshore. It is not clear that the dominant northeastward wind during early August on the West Florida Shelf would explain the eastward movement of the edge of the Loop Current traced by its associated color band, as evidenced in Figs 2-4. It is possible that the northward and westward wind during early to mid-August in the Florida Straits may have helped push the color band closer to the coast. However, these are deep and very massive flows and it is difficult for winds to be the prime cause for such changes in flow.

The strong northward and northwestward wind in late August, and subsequent wind in early September (Fig. 11) around the dispersal area may have contributed to dissipate the river plumes, which are shallow and less dense water masses relative to the oceanic water in the Gulf. This dissipation was also facilitated by the shedding of a Loop Current eddy, which led to the contraction of the Loop Current to the south, the westward shift of the eddy, and therefore the mechanism to advect water off the shelf north of the dispersal area.

It is not clear if these stronger westward and northwestward winds during the week of 27 August (Fig. 11) would be partly responsible by the westward movement of the eastern edge of the Loop Current revealed by the contrast between Figures 4 and 5. This shift may be more closely associated with the westward translation motion of the anticyclonic eddies shed by the Loop Current.

Starting in early September (Fig. 5), a Loop Current eddy shedding process was taking place and was completed by early October (Fig. 8). The shed anti-cyclonic (clockwise) eddy (Fig. 8) remained stable but the northern tip of the Loop Current retreated to the southernmost position at about 24.7^{o}N.

The large-scale circulation features, the eddy shedding process, and the eddy stagnancy are confirmed by the Sea Surface Height (SSH) data from satellite altimeters (data courtesy of Bob Leben of U. Colorado, http://www-ccar.colorado.edu/~realtime/), as shown in Figures 12-14.

The large-scale features documented here represent major dominant biogeochemical and physical conditions over our study area.

Small-scale Features

Following the Loop Current pathway and in the Florida Straits, there have been some small-scale water color patches of interest. Many of these occurred near the Florida Keys since late August, as shown in Figure 15. These patches may have resulted from one or more of the following mechanisms: river plume water moving along the edge of the Loop Current, local upwelling from small eddies, or water intrusion from Florida Bay (see the 09/02/03 image in Fig. 15). Chlorophyll concentrations in these color patches range from 0.15 to 0.5 mg m^{-3}, compared with <0.1 mg m^{-3} in the nearby Gulf Stream waters.

Note that algal blooms near the Florida Keys National Marine Sanctuary (FKNMS) may lead to ecosystem stress. As an example, the spring 2002 "black water" event in Florida Bight (bay side of the Florida Keys) was thought to cause a decline in coral reef health and sponge die-offs found subsequently (Hu et al., 2003a). However, the elevated chlorophyll near the Keys at this time by no means was analogous to the 2002 "black water" event. The perceived cause of the "black water" was both an earlier red tide and local river runoff (SWFDOG, 2002); it lasted for about four months and contained high levels of chlorophyll (5-10 mg m^{-3}) and CDOM (~0.3 m^{-1} at 400 nm) and also red tide species of up to 10,000 cells/L. In contrast, the colored patches near the Keys (ocean side) during this Piney Point study contained chlorophyll and CDOM of about 0.15-0.5 mg m^{-3} and 0.02-0.05 m^{-1}, respectively (the nearby clear, Gulf Stream waters contain about 0.08 mg m^{-3} and 0.015 m^{-1}, respectively). This is an order of magnitude smaller. Yet, we are monitoring these waters to understand whether any of the wastewater dispersed far to the north may come in contact with the Keys.

Piney Point Water Detected?

The whole dispersal area (outlined as a white box in Figs. 1-9) and its immediate downstream area (south of the dispersal area) remained under consistent influence of river plume water and/or productive water carried along the Loop Current until early October. It is therefore impossible to distinguish if any enhanced color in the area is from the discharged treated wastewater. From early October, although the discharge area is free of the river plume and Loop Current color interference, scattered clouds within the dispersal area and cloud-adjacency effects in the algorithms to generate the ocean color data make it difficult to determine if there is immediate biological effect within the dispersal area and in its immediate downstream waters (i.e. to the south). The relatively cloud-free images, particularly those concurrent with the barge discharge dates, have been examined by zooming and color bands were stretched to see if there is any color effect from the discharge. Results are inconclusive, i.e., there is no solid evidence that the discharge has led to a color change.

We posed the following question: Is it possible that the discharged Piney Point water may have contributed to a color change in and around the dispersal area? From a nutrient budget point of view the contribution, if there is any, is likely to be very small and possibly negligible. From sample analysis of the barge water and nutrient budget estimates, if the discharged water is diluted rapidly the biological and color effects, if any, may not be detected by satellites. Samples taken from the Piney Point treated water on the barge show that absorption coefficient of colored dissolved organic matter (CDOM or a mixture of naturally-occurring tannic and fulvic acids) at 400 nm (ag400, a proxy for CDOM concentration in the sample) is about 1.14 m^{-1}. For reference, Mississippi water at the mouth of the river delta at this time of the year is about 1.9 m^{-1}; the open Gulf clear water is about 0.03 - 0.04 m^{-1}. Phosphorus concentration was about 340 mg m^{-3} in the treated wastewater. A simple dilution of 1:2000 within a few hours (according to EPA's plume model) would result in an addition of 0.00057 m^{-1} for CDOM and 0.17 mg m^{-3} for phosphorus, respectively. This level of CDOM cannot be detected by satellites or even with sensitive ground-based equipment after such dilution. Based on the measured phosphorus:chlorophyll ratio (1.7 weight:weight; Vargo et al., in review), the discharged phosphorus can support chlorophyll growth of up to 0.1 mg m^{-3} after the dilution, which is comparable to the background level of the clear water in the open Gulf. Further dilution, such as that which may be affected by mixing and dispersal along the strong Loop Current, would make any possible accumulation of algae biomass due to growth by such nutrient addition undetectable.

However, if the water had been stagnant and nutrients were to be added continuously to the same location, then there would have been a possibility for detection after some time. The satellite data was instrumental in finding the location of fast and massive currents that would lead to rapid and continuous advection and dilution of wastewater far away from the coast and shelf environments.

Algal Bloom Detected?

Because the primary purpose of the monitoring was to document whether there was any impact of the discharge on our near-shore environment, a long-term change detection study was designed and implemented for several shelf and coastal waters.

We chose six areas (see Figure 9: Areas #1 to #6) to detect whether there was enhanced biological activity relative to pre-dispersal conditions as well as to what has been found in these regions at the same time of the year in previous years. Areas 1 to 3 are on the West Florida Shelf (WFS), one in water depth < 30 m (waters with extreme turbidity/bottom interference were excluded to improve quality control), one in 30-50m, and one in 50-100m off central western Florida. Area 4 is in the Florida Strait in water depth 200-500m. Area 5 is closer to the coast and covers only the near shore waters of the lower Keys. Area 6 is to the southeast of the dispersal area in deep waters and also overlapping the deep shelf. The surface area for each area of interest sampled is about 6450, 7213, 12708, 4892, 3097, and 37660 km^2, respectively.

Monthly mean satellite ocean color data spanning the period September 1997-October 2003 were derived from SeaWiFS (McClain et al., 1998) with a semi-analytical algorithm (Carder et al., 1999; Hu et al., 2003b). The following products are shown in Figures 16 - 18:

- surface chlorophyll concentration in mg m^{-3} and
- CDOM absorption coefficient at 443 nm in m^{-1}.

These data have been validated by extensive cruise surveys (Hu et al., 2003b). The uncertainties of the values measured are generally within ±35% for the deep water (> 30 m) where there is no significant riverine impact. The near shore values, particularly close to the coast (waters shallower than 30 m) are likely less accurate.

Our results show that none of the six areas has shown significant increase in chlorophyll concentration since the dispersal was initiated on 20 July 2003. This shows that shelf and coastal waters have similar phytoplankton concentrations this year when compared to other years during the period of the discharge. There were several cases when elevated colored dissolved organic matter (or CDOM) was seen:

1) Area 1 in September 2003 - this may be an indication of terrestrial runoff that carries excessive amount of CDOM;
2) Area 3 and Area 4 in August 2003 – this indicates significant influence of the Mississippi plume or other northern rivers, as shown in the images of previous reports;
3) Area 6 in July and August 2003, which is also due to river plume.

The abnormal behavior of the year 1998 in terms of higher concentrations of CDOM and higher riverine influence is possibly related to El-Nino, which was associated with unusually high rainfall in the drainage basins for these rivers.

The areas in this study were carefully chosen to represent all potential affected areas. They were chosen to optimize spatial coverage and minimize the number of graphs required to present time series for the region. Clearly, it would be impossible to present similar graphs for every pixel in the study area. However, such analyses can be performed for any particular location. For example, we received a report of possible water quality degradation from a fishing boat captain, which prompted us to focus a time series analysis (1997 – 2003, see Report #3) of the water clarity at the reported location to the northeast of the Dry Tortugas. The satellite images showed that the drop in water clarity was indeed due to the river plume being advected all the way from the coast of the northern Gulf of Mexico.

From the above analysis, we concluded that there was no evidence of *widespread* increase in phytoplankton growth or concentration between August and September 2003 in areas downstream of the wastewater dispersal zone. The increase in CDOM for Area 3 on the WFS and for Area 4 in the Florida Straits is due to the influx of river-derived waters originating in the northern Gulf of Mexico.

In all areas examined, the chlorophyll and CDOM levels are similar to those seen in other years and should be considered normal.

Where Does The Water Go?

The MODIS ocean color imagery clearly shows that the discharge area is within the influence of the Loop Current, i.e. either near the Loop Current edge or within the Loop Current itself or within a large anti-cyclonic eddy (as the one shed in early October 2003). We therefore inferred that the discharged water moved to the south/southeast, carried by the Loop Current, and that it moved to the Florida Straits and then into the Atlantic Ocean by the Gulf Stream along Florida's east coast. Such motion is mimicked by numerical computer models (http://www7320.nrlssc.navy.mil/IASNFS_WWW/today/IASNFS_gom.html#wfs) and confirmed by direct observations from surface drifters and satellite altimeter data, as shown in Figs. 2-5 and Figs. 7-8. Only one of the ten surface Argo drifters, released in the dispersal area on different dates by Dr. Robert Weisberg's group (USF), moved to the north (float #20087, see Report #10). This drifting float did not reach the coast either. One drifter was caught in the anticyclonic eddy (Fig. 8). Most of the drifters moved to the south and ended up in the Atlantic.

The southeastward transport of river discharge water in the Gulf of Mexico has been observed repeatedly every year since 1998 when SeaWiFS data became available, although the timing and strength varied from year to year. Figure 19 shows a SeaWiFS composite chlorophyll image from July 24th to July 29th 1999. The water trajectory outlined by the yellow and green colors offshore and along the WFS shelf break is remarkably similar to what was observed in early August 2003. Such a flow pattern in the northern Gulf is driven mainly by entrainment of shelf water in the northern Gulf of Mexico into the Loop Current, and less by wind and surface heat flux. During the spring, offshore transport of shelf water in the northeastern Gulf takes place immediately south of Cape San Blas and in this case the driving mechanism is the density difference between the cold shelf waters and the warm offshore waters (Yang and Weisberg, 1999; He and Weisberg, 2002).

Temperature Imagery

Daily images of Sea Surface Temperature from AVHRR and MODIS have been generated, broadcasted online, and examined. These images did not reveal much information, as SST is typically homogeneous in the Gulf at this time of the year. Only until late September and early October did the images start to show large-scale features such as the large eddy and the Loop Current. These images complement the ocean color imagery for large-scale feature identification, as the four AVHRR sensors and two MODIS sensors increase the spatial coverage and minimize the cloud covers.

Field Samples

Sample analysis is necessary to provide direct evidence of the biological and chemical content of the water. Most of the samples collected for the Piney Point offshore discharge program have been analyzed by other groups at USF and Florida Marine Research Institute (for red tide organism analysis), and results will be posted separately. Our water sampling effort focused on the water CDOM content, mainly to help interpret the satellite signal, because the color of the river plume water is due in a large part to CDOM. CDOM is also used to trace fresh water, as elevated CDOM often indicates presence of river plumes.

The samples were taken mainly from the fourteen pre-determined stations. Figure 20 shows a MODIS chlorophyll image for 26 August 2003 with station locations overlaid. The image shows that there appear to be two river plumes: one crossing the western part of the dispersal area and one to the east of the box. This has been confirmed with nearly concurrent field data. Figure 21 shows CDOM absorption, salinity, and chlorophyll concentrations in surface waters from the 27-28 August survey. Similar data from the 3-4 September survey are shown in Figure 21 (chlorophyll and salinity data courtesy of Ms. Danylle Spence-Ault and Dr. Gabe Vargo of USF).

Because the satellite data and field surveys are not strictly concurrent, and because of the eastward movement of the Loop Current edge, although in Fig. 20 it would appear that ST 7 and ST 8 are located in high-chlorophyll water, field data show low chlorophyll, low CDOM, and high salinity for these two stations. The river plume on the eastern side of the dispersal area was confirmed by the low salinity, high CDOM, and high chlorophyll data from the cruise survey.

The increase of chlorophyll from high-salinity Gulf waters to low-salinity plume waters is proportional to that of CDOM, both by a factor of 2-3 (Figs 21-22). This implies that there was no significant "new" chlorophyll growth, but rather shows a mixing process. Typically, waters with "new" chlorophyll tend to have elevated chlorophyll but rather stable CDOM. We have only limited sample data available at this time and more results are required for further interpretation. Such data and interpretation will be presented in the near future when data are processed.

Conclusion

For the period of 20 July to 13 October 2003, nineteen barge trips were made and approximately 122 million gallons of treated Piney Point wastewater were discharged in the Gulf. Through analysis of satellite imagery (ocean color, altimetry, and temperature), field samples, and ancillary data such as wind and river discharge, we did not observe any apparent impact of the Piney Point discharge on either chlorophyll concentration or CDOM content on the West Florida Shelf or near the Florida Keys. Concentrations of both phytoplankton and CDOM are comparable to those observed in five previous seasons (1998-2002). The chlorophyll and CDOM levels in the areas examined in 2003 should be considered normal. We attribute this to relatively low total nutrient and water volume released from each discharge, as compared with that from the Mississippi River, and rapid dilution by ocean currents such as the Loop Current. Indeed, the Mississippi River water enters the Florida Strait every year since 1998 when SeaWiFS data became available, although the timing and strength vary from year to year.

The long-term change analysis was performed over large areas (> 3000 km^2) to optimize spatial coverage and minimize the number of graphs required to present time series for the region. The results and the above conclusion should therefore be interpreted only on a synoptic sense. At any particular location, an anomaly, if there is any, might be identified. An effort is being carried out to identify potential anomaly events at all locations, and results will be presented in future reports.

Satellite data analyses have provided real-time and accurate information on the position of the major currents that would carry materials away from the dispersal region and minimize any possible coastal impact. The satellite data were instrumental prior to the initiation of the dispersal to outline the area where the barge would operate to disperse the treated wastewater. Without the weekly satellite data analysis it would be impossible to tell which way dispersed waters are likely to move in a synoptic fashion, and therefore whether any dispersed materials would stagnate or re-circulate at the dispersal site. Furthermore, historical satellite data provide the unique baseline information that is critical to evaluate that under what circumstances the oceanographic condition should be considered as "normal."

Acknowledgements

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Figures

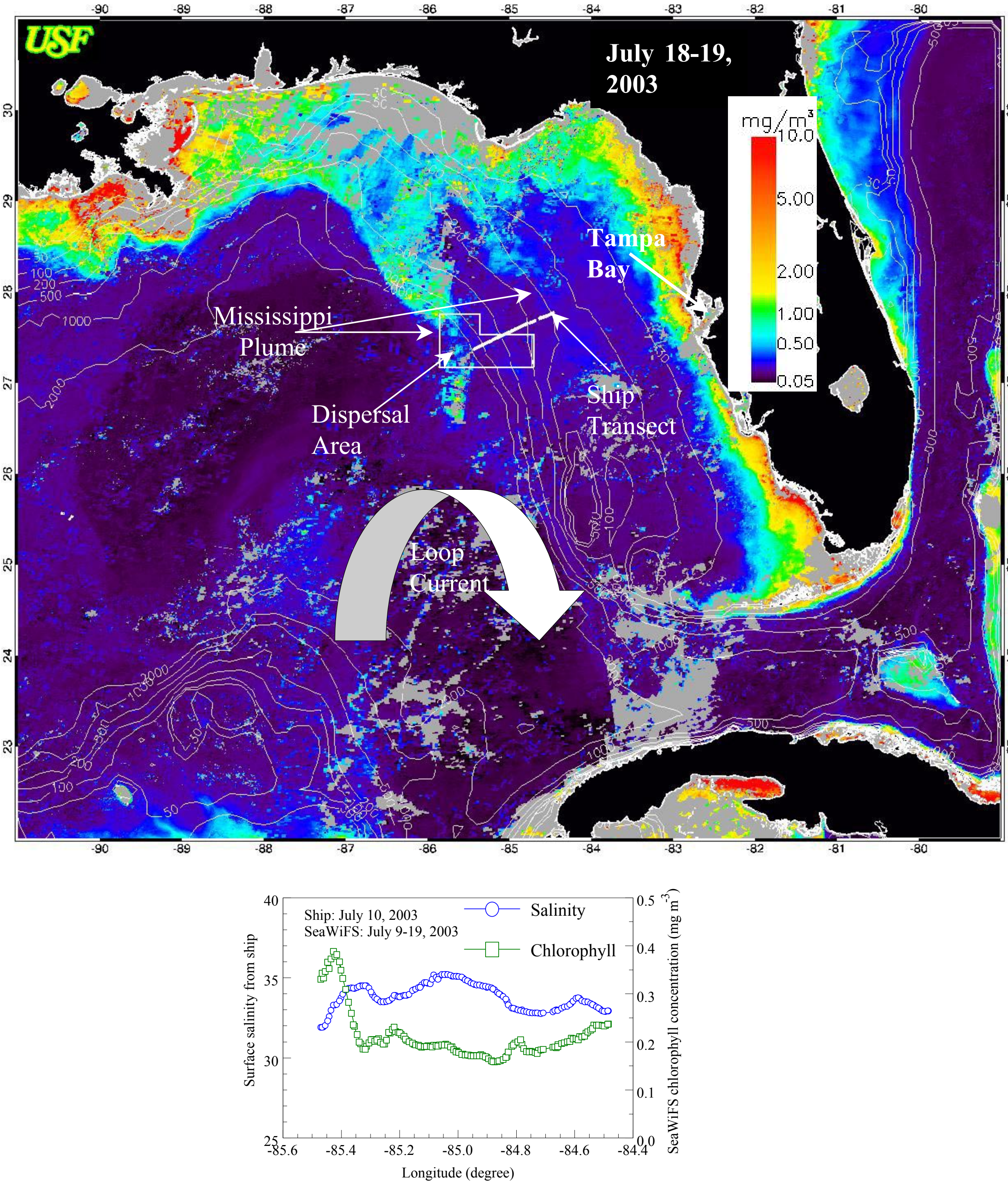

Figure 1. Top: MODIS chlorophyll image for 18-19 July 2003, before initial dispersal on 20 July. The dispersal area is outlined as a white box. Also overlaid are the bathymetry contours, from 30 to 2000 m. One major current, the Loop Current, is outlined on the image. A ship transect, which detected low salinity (32-33, bottom figure) waters at the beginning and end, is overlaid on the image.

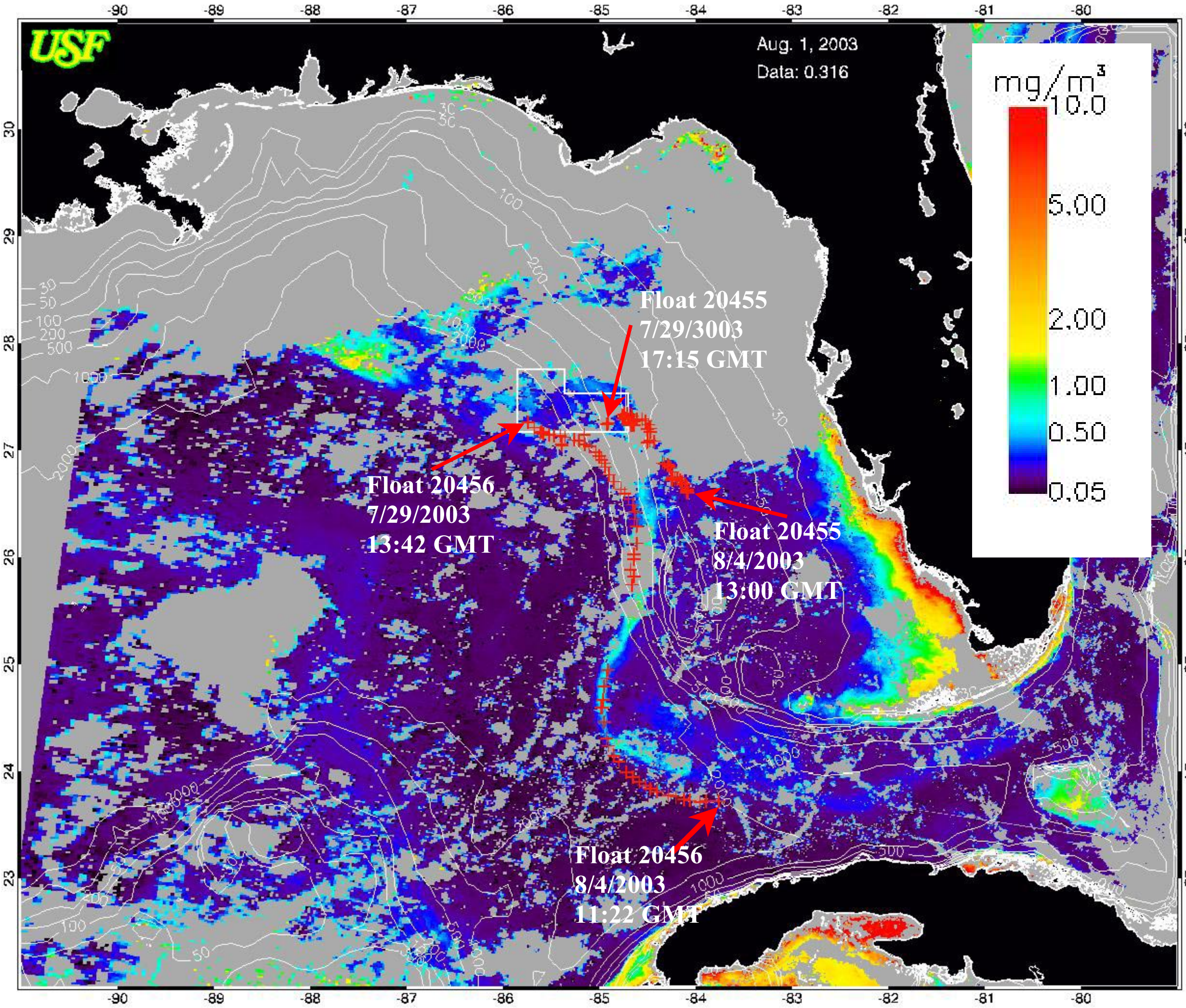

Figure 2. MODIS chlorophyll satellite image captured on 1 August 2003, when more than 16-million gallons of treated wastewater had been dispersed in the area outlined by the white box beginning on July 20th, 2003. The enhanced color south of the dispersal area is evidence of enhanced biological activities along the edge of the Loop Current whether upwelling occurs (the Loop Current is the are of low chlorophyll concentration or darker blue in the middle of the eastern Gulf of Mexico). This very significant biological enhancement is likely the result of nutrients provided by the upwelling phenomenon. Enhanced colors around cloud edges are algorithm artifacts. Overlaid on the image are the locations of two Argo floats (red crosses. Argo data courtesy of Mr. Jason Law and Dr. Robert Weisberg of USF.) that flow with the currents. Also overlaid on the image are bathymetry (water depth) contour lines. The difference between the float position and the color patch position around 24°N 84.5°W is due to the southward movement of the water mass from 1 August (image date) and 4 August (float date). This effect is more apparent in Figure 3.

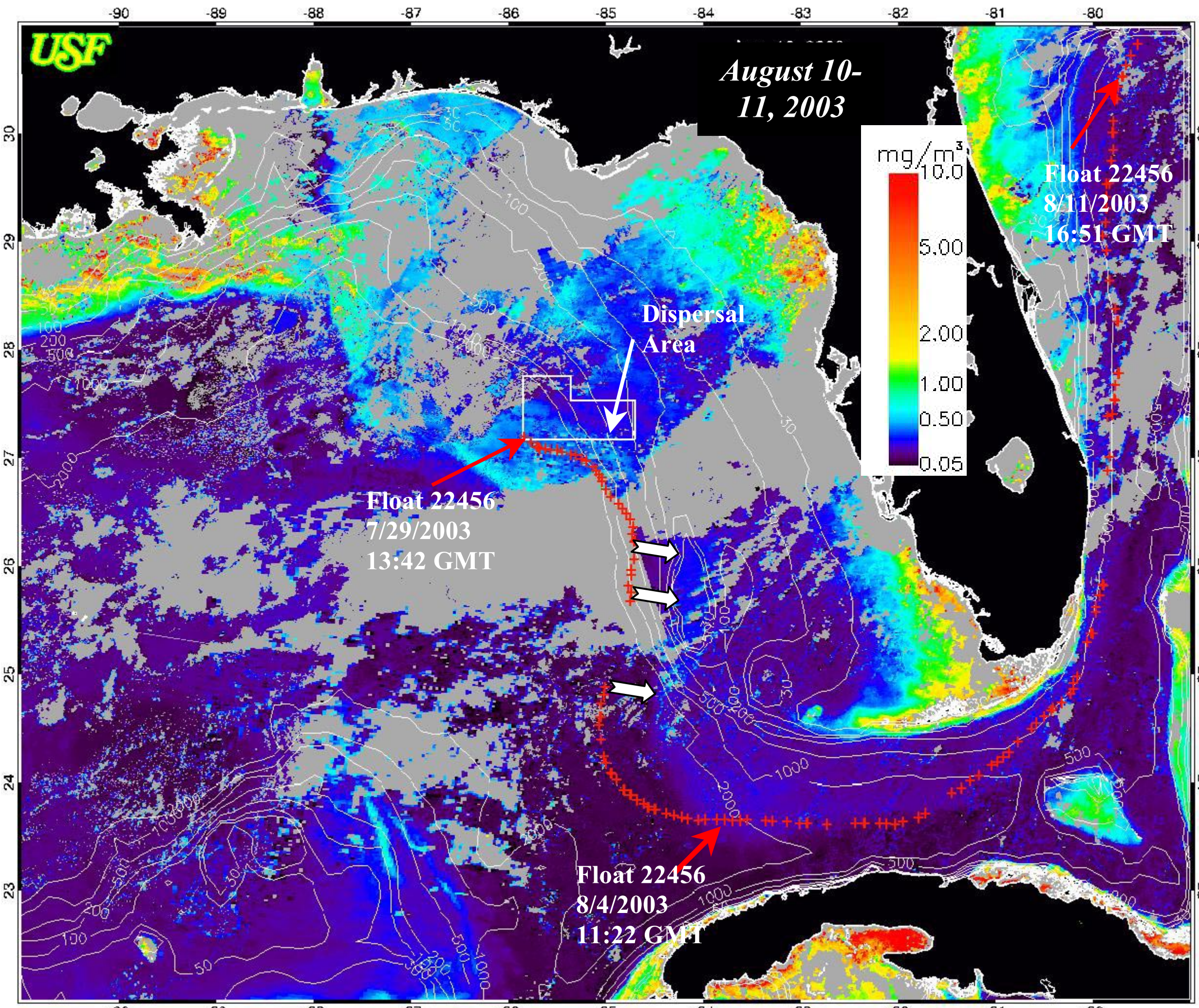

Figure 3. MODIS chlorophyll image for 10-11 August 2003, when about 27-million gallons of *treated* wastewater had been dispersed in the area outlined by the white box beginning on 20 July 2003. Overlaid on the image are the locations of one Argo drifter (red crosses. Argo data courtesy of Mr. Jason Law and Dr. Robert Weisberg of USF) that tracked currents. Difference between image and drifter dates is shown as a difference in the location of the drifter track and the edge of the Loop Current. This difference shows how far the edge of the LC moved toward Florida over a short period, in the direction indicated by the white arrows.

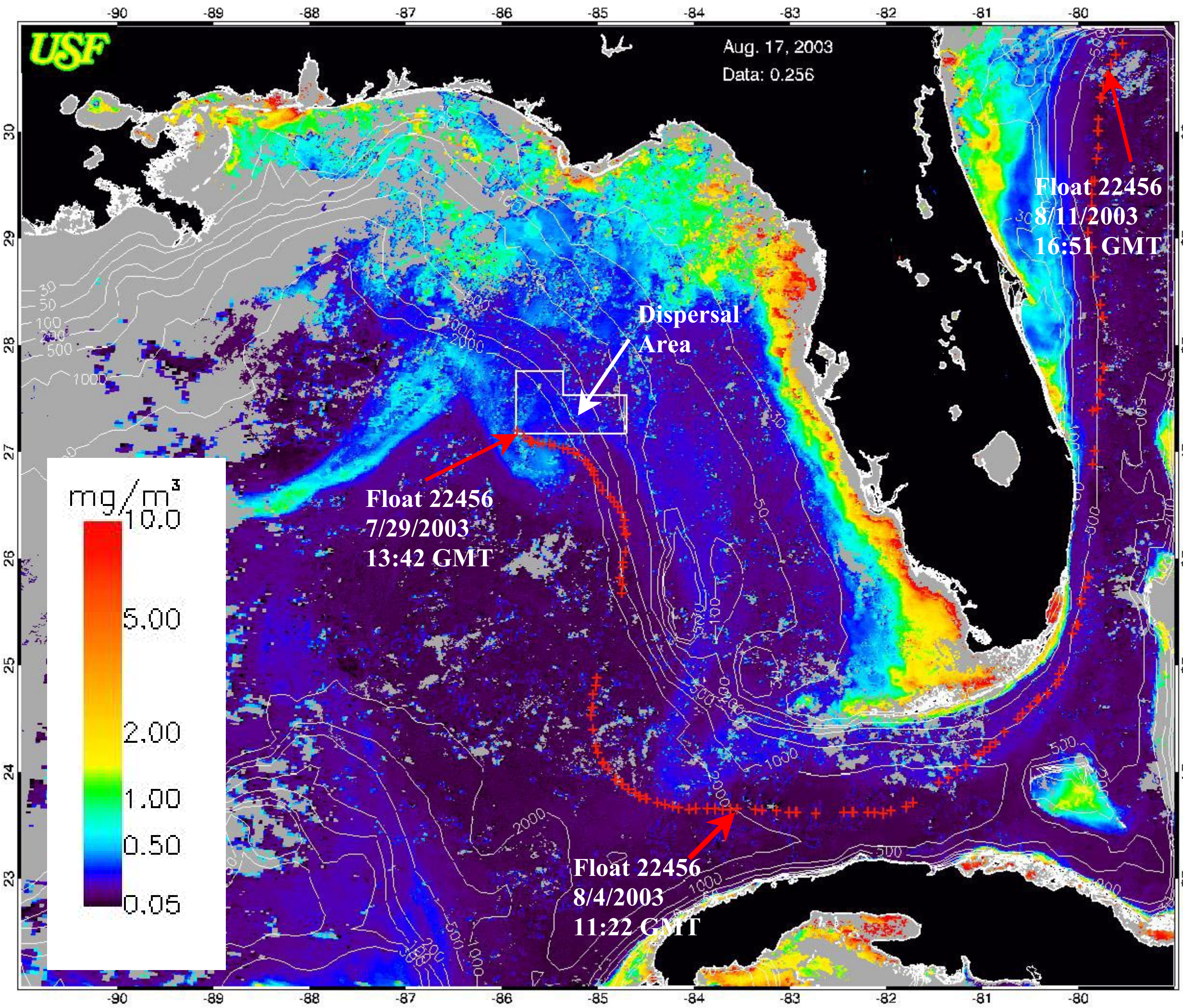

Figure 4. MODIS chlorophyll composite (11:53am and 3:02pm) satellite image for 17 August 2003, when about 40-million gallons of treated wastewater had been dispersed in the area outlined by the white box beginning on 20 July 2003. Overlaid on the image are the locations of one Argo float (red crosses. Argo data provided courtesy of Mr. Jason Law and Dr. Robert Weisberg of USF). Also overlaid on the image are bathymetry (water depth) contour lines. The color band tracing the edge of the Loop Current in the Florida Strait south of the Dry Tortugas moved to the north as compared to its position on 10-11 August (see Fig. 3).

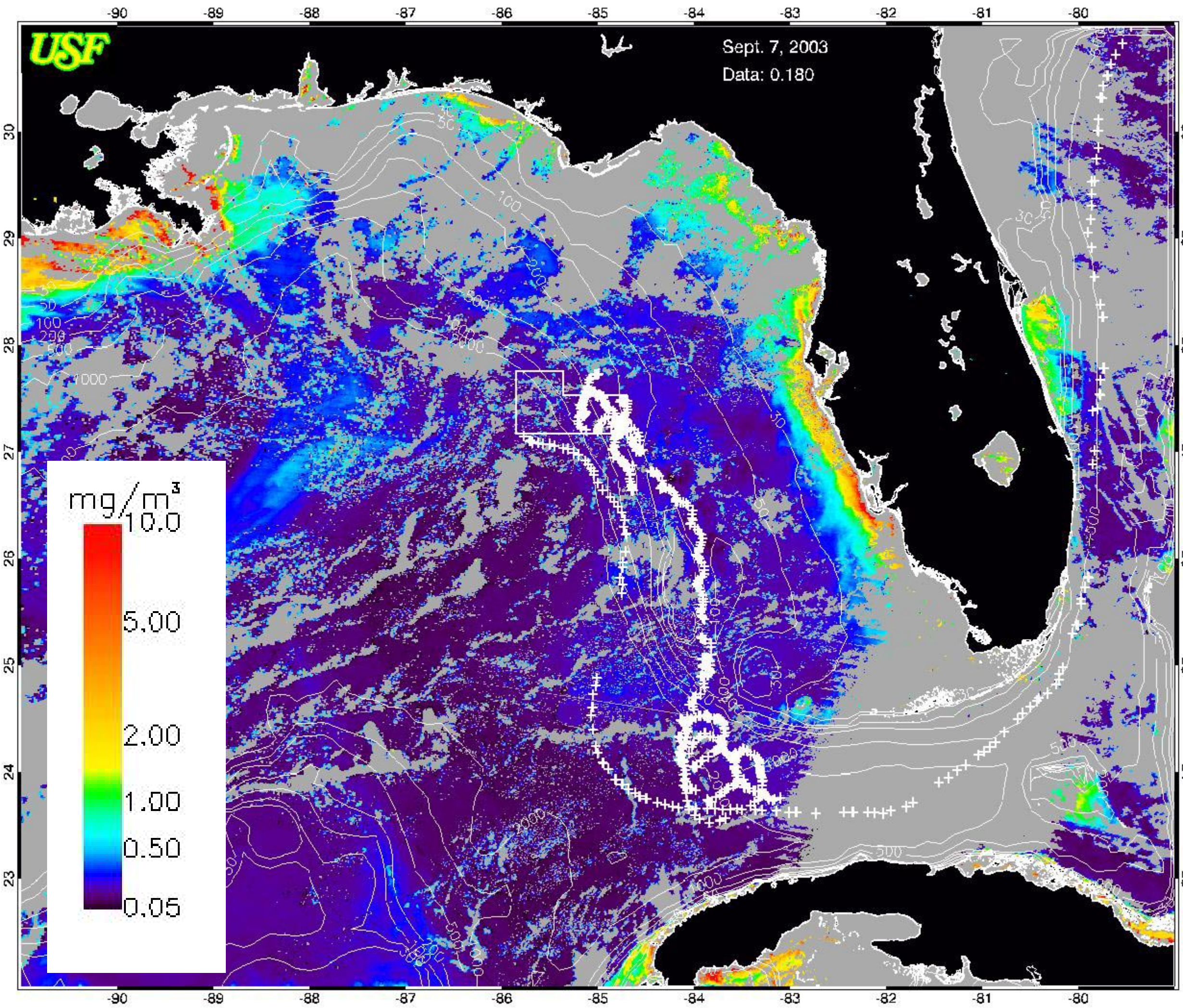

Figure 5. MODIS satellite-derived "chlorophyll" product for 7 September 2003. Overlaid on the image are the tracks of six Argo floats (white crosses. Argo data courtesy of Mr. Jason Law and Dr. Robert Weisberg of USF). These drifters show the general movement of water and currents from late July to early September 2003. Also overlaid on the image are bathymetry contour lines (water depth) and the outlines (white box) of the dispersal area. The color band along the eastern Loop Current edge becomes more diffused on the West Florida Shelf.

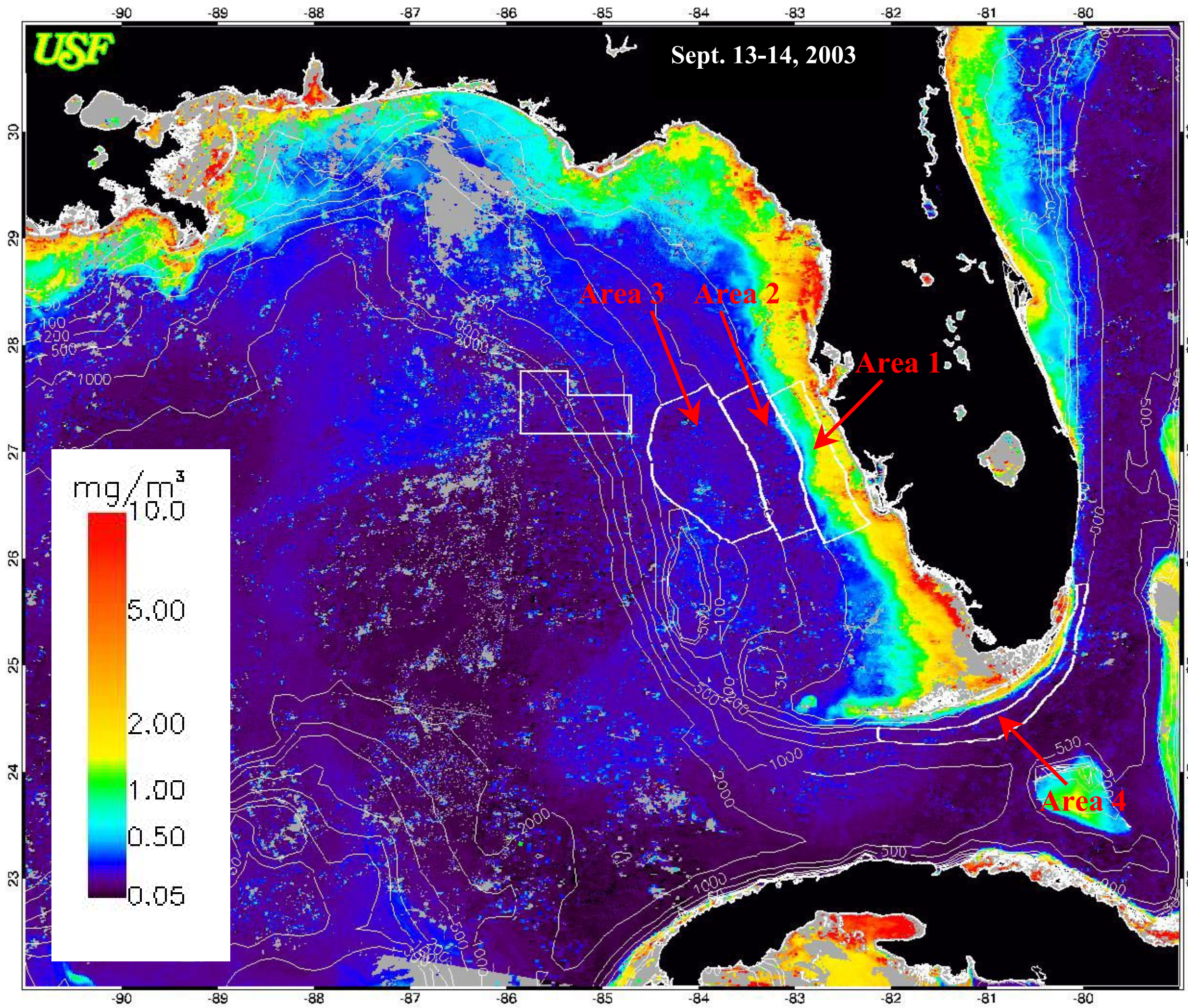

Figure 6. MODIS satellite-derived "chlorophyll" product for 13-14 September 2003. Overlaid on the image are bathymetry contour lines (water depth) and the outlines (white box) of the dispersal area. Areas 1 to 4 were selected to study long-term color changes over a period of seven years, to establish a baseline prior to the dispersal of Piney Point wastewater.

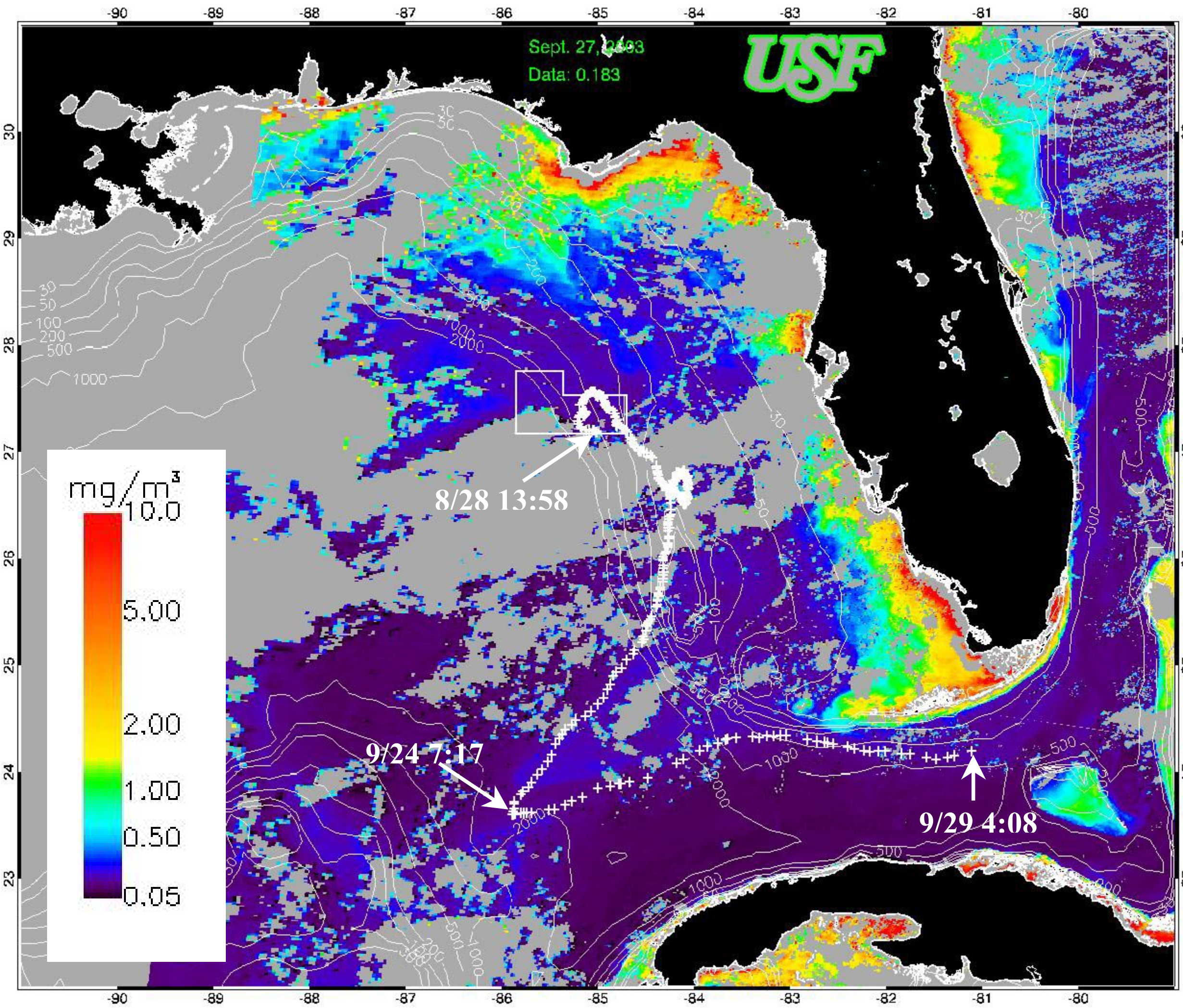

Figure 7. MODIS satellite-derived "chlorophyll" product for 27 September 2003. Overlaid on the image are the outlines (white box) of the dispersal area, the water depth contours (30 – 2000 m), and the flow tracks of a surface drifter (Argo #39764). Argo data courtesy of Mr. Jason Law and Dr. Robert Weisberg of USF. A large eddy is being shed from the Loop Current.

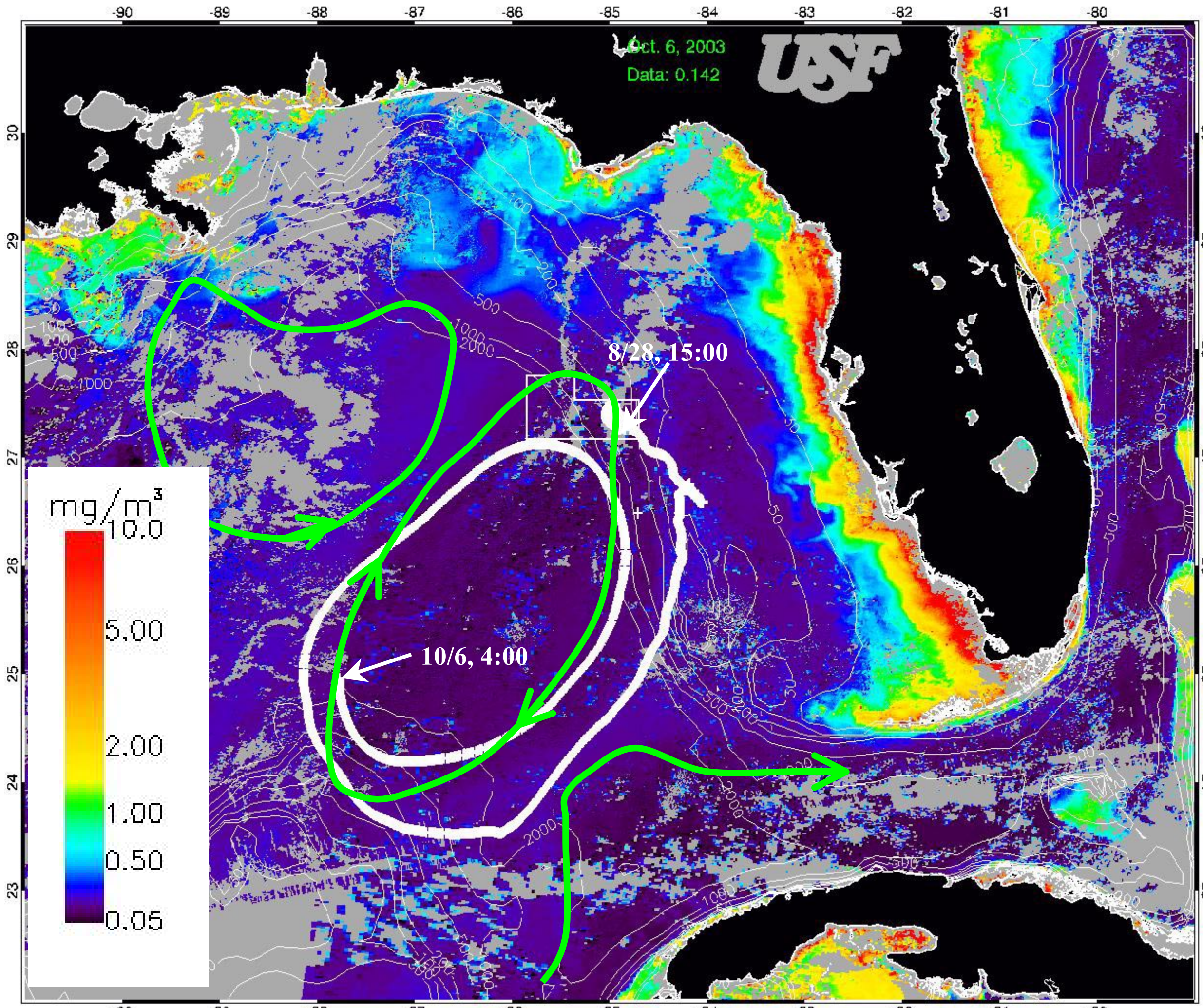

Figure 8. MODIS satellite-derived "chlorophyll" product for 6 October 2003. Overlaid on the image are the outlines (white box centered at about 27.2°N 85.5°W) of the dispersal area, the water depth contours (30 – 2000 m), the Loop Current pathway, and a pair of anti-cyclonic (clockwise) and cyclonic (counter-clockwise) eddies. Green lines with arrows are manually drawn based on ocean color data only and validated using satellite radar altimeter data. The water movement tracks detected by Argo float # 20089 (data courtesy of Mr. Jason Law and Dr. Robert Weisberg of USF) are shown as white spiraling lines.

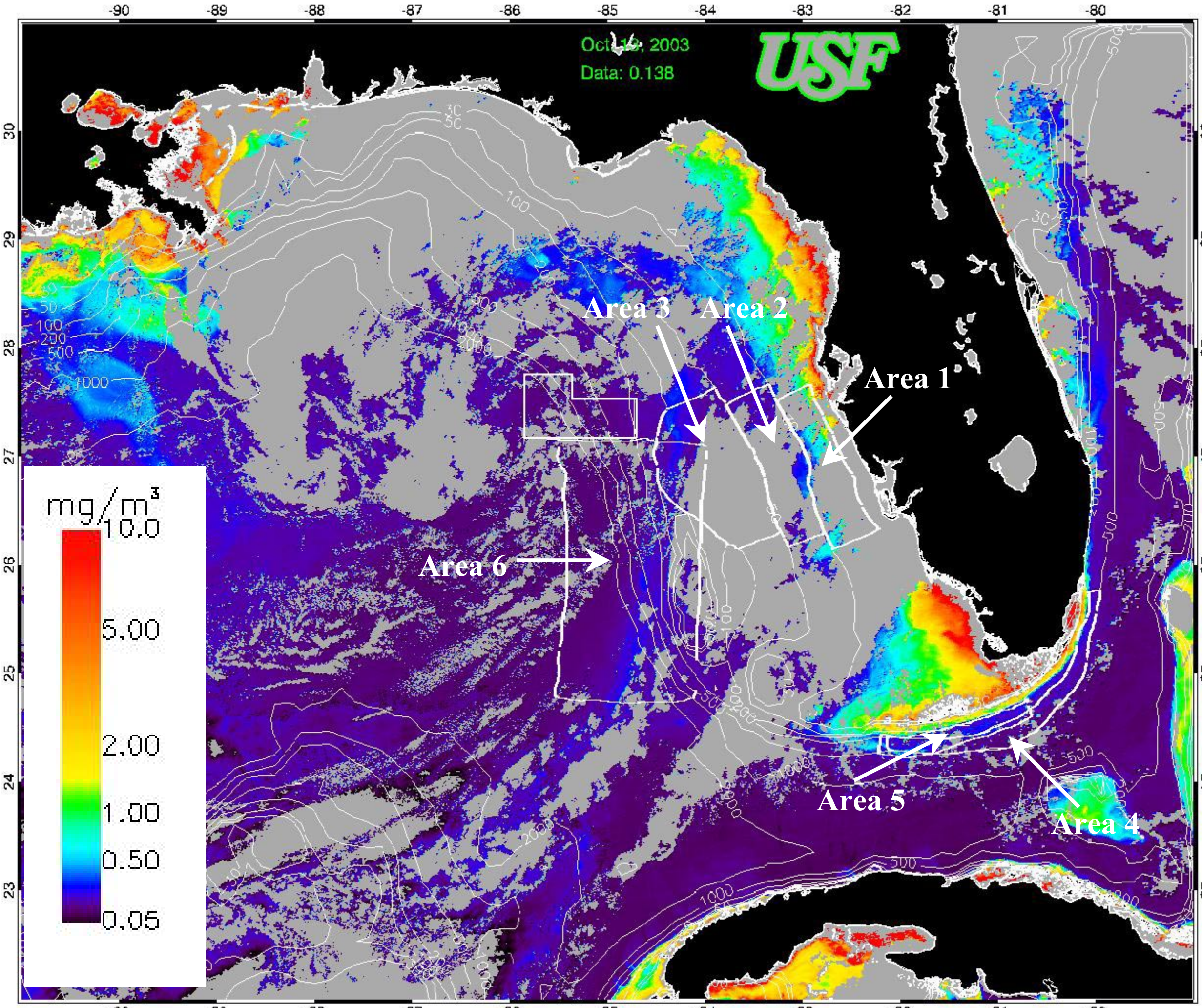

Figure 9. MODIS satellite-derived "chlorophyll" product for 13 October 2003. Six areas are chosen to study the color changes through time. See text for details.

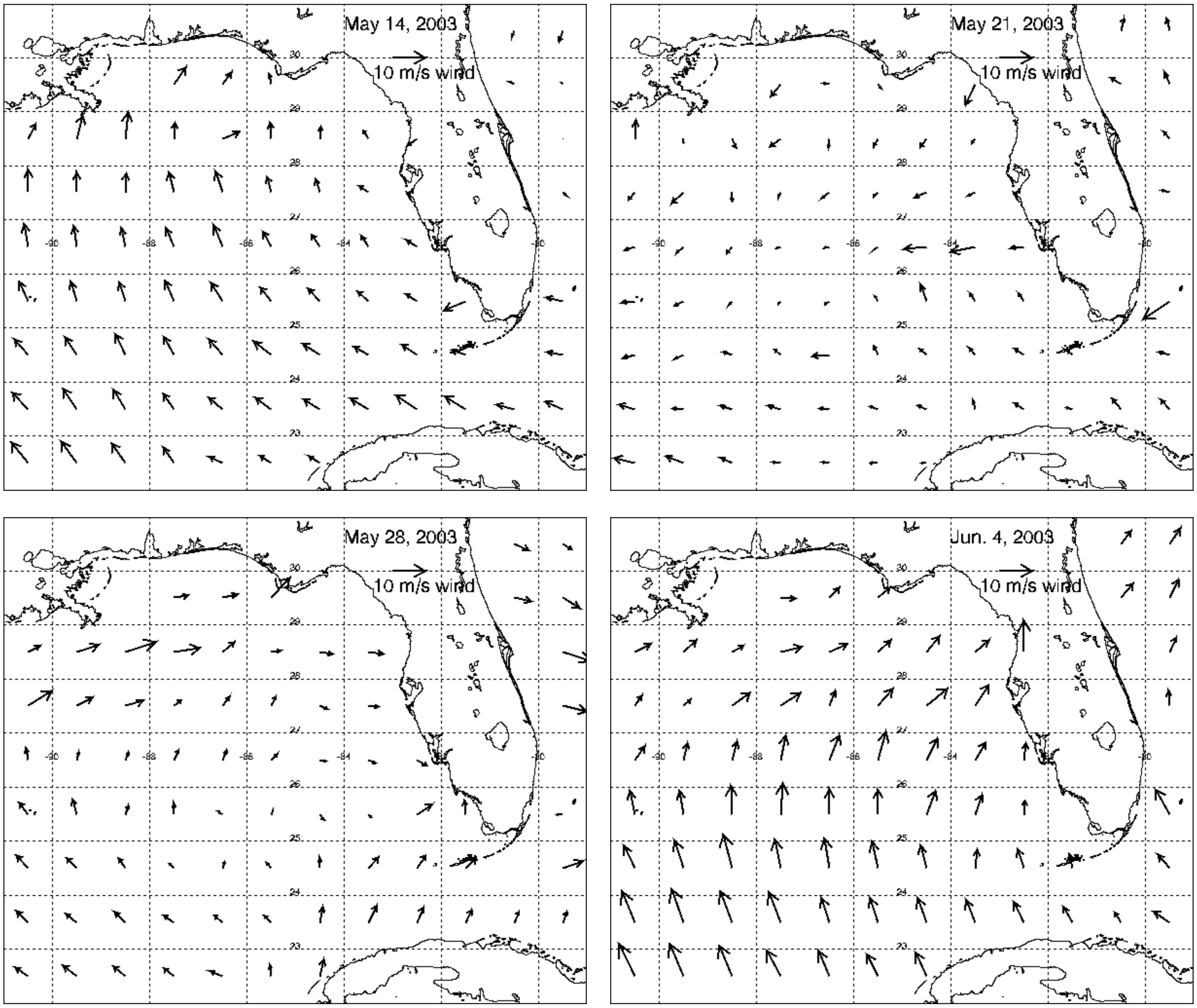

Figure 10. Weekly mean wind from SeaWinds/QuikSCAT radar scatterometer satellite sensor (date shows beginning of the week).

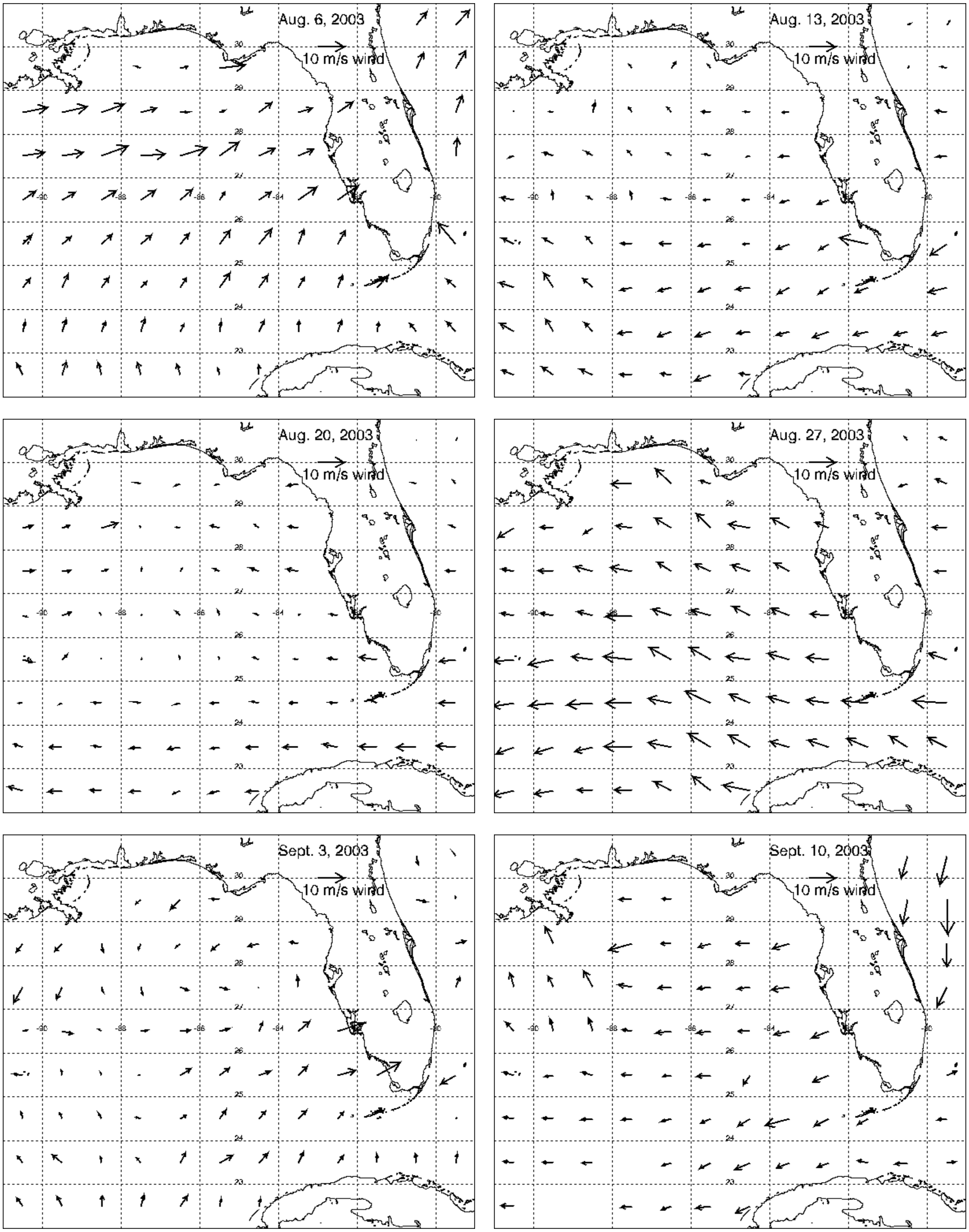

Figure 11. Weekly mean wind from SeaWinds/QuikSCAT (dates show beginning of the week).

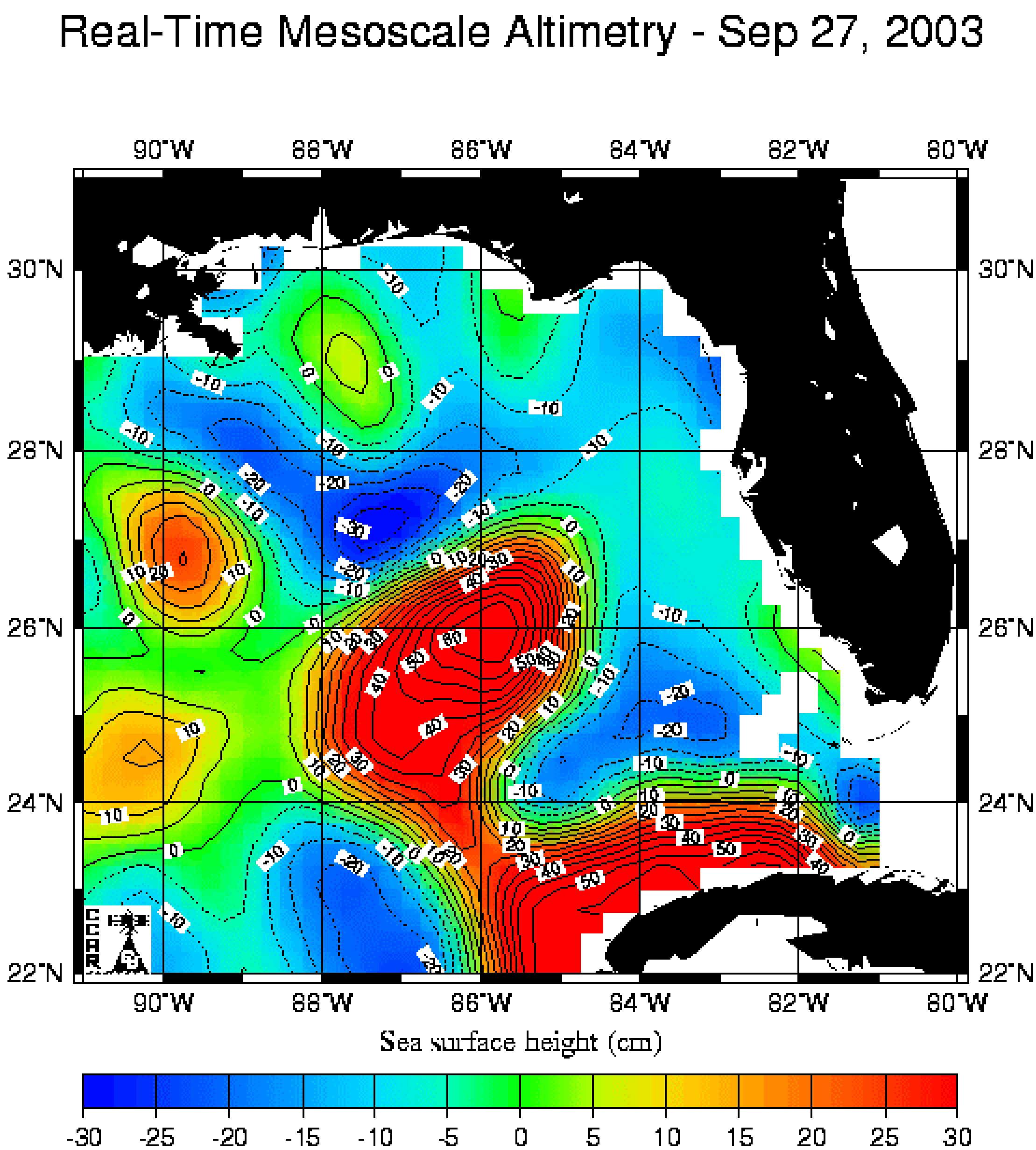

Figure 12. Sea Surface Height (SSH) from satellite altimeters for 27 September 2003 (data courtesy of Dr. Bob Leben of U. Colorado, http://www-ccar.colorado.edu/~realtime/).

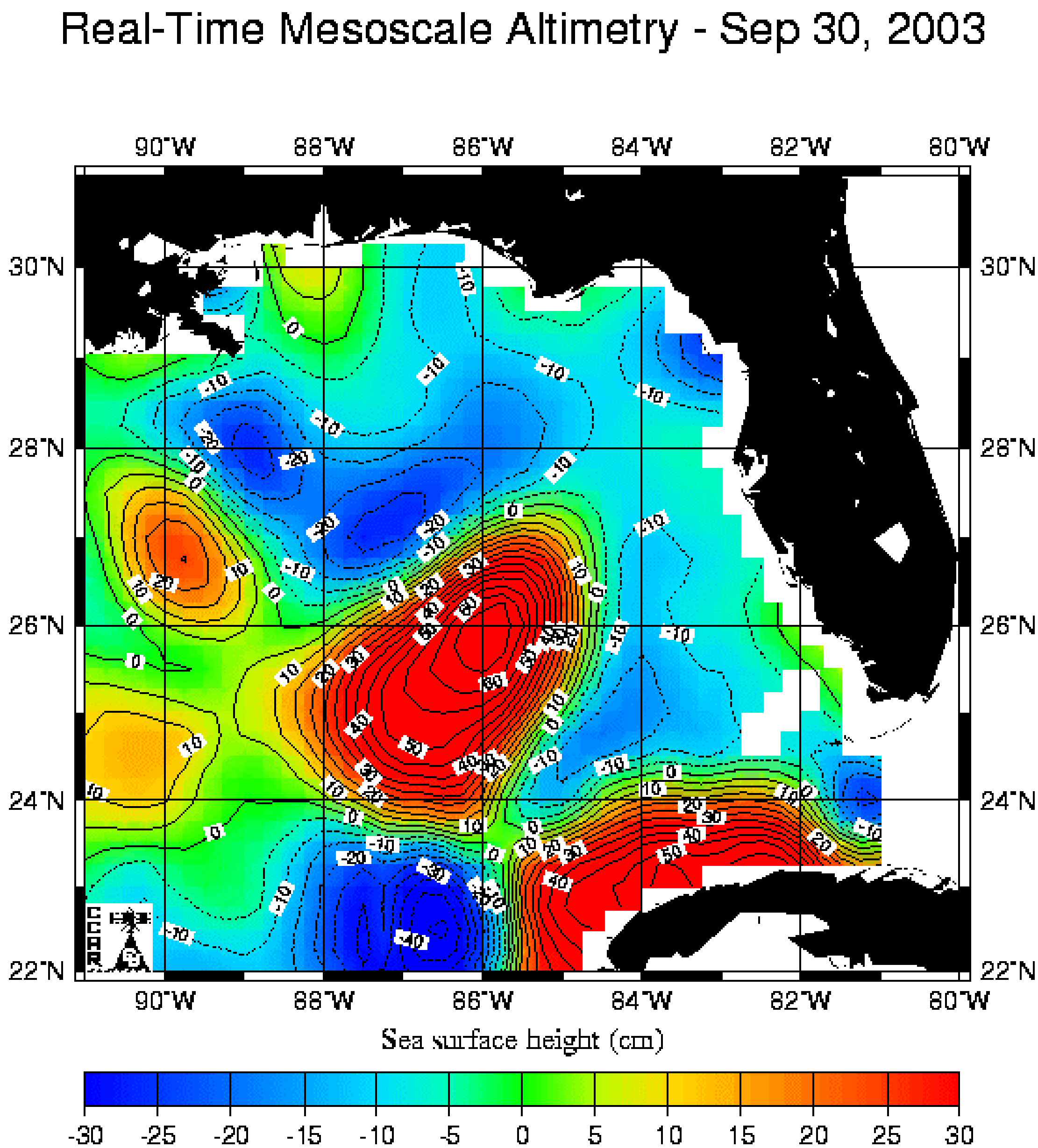

Figure 13. Sea Surface Height (SSH) from satellite altimeters for 30 September 2003 (data courtesy of Dr. Bob Leben of U. Colorado, http://www-ccar.colorado.edu/~realtime/).

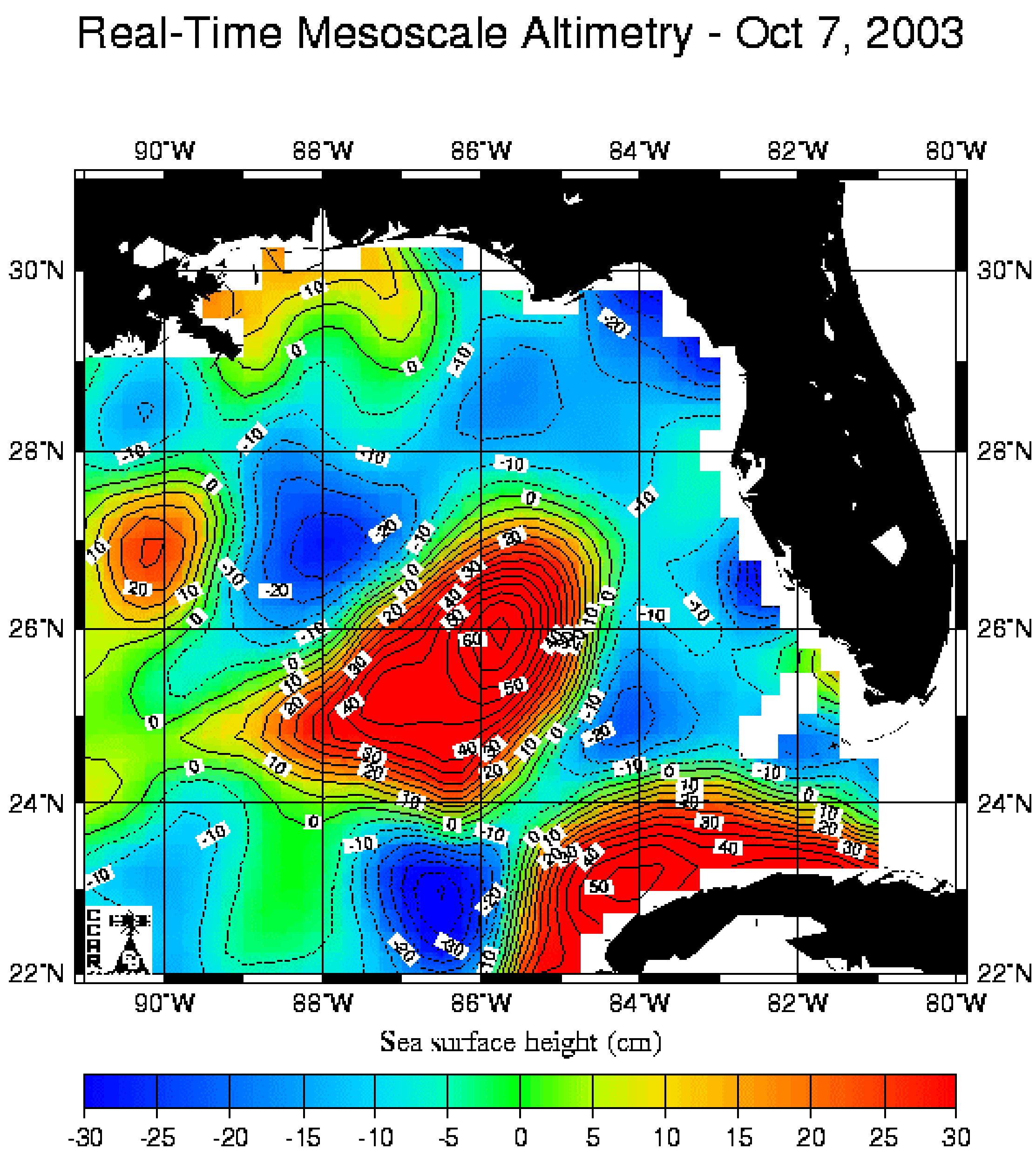

Figure 14. Sea Surface Height (SSH) from satellite altimeters for 7 October 2003 (data courtesy of Dr. Bob Leben of U. Colorado, http://www-ccar.colorado.edu/~realtime/).

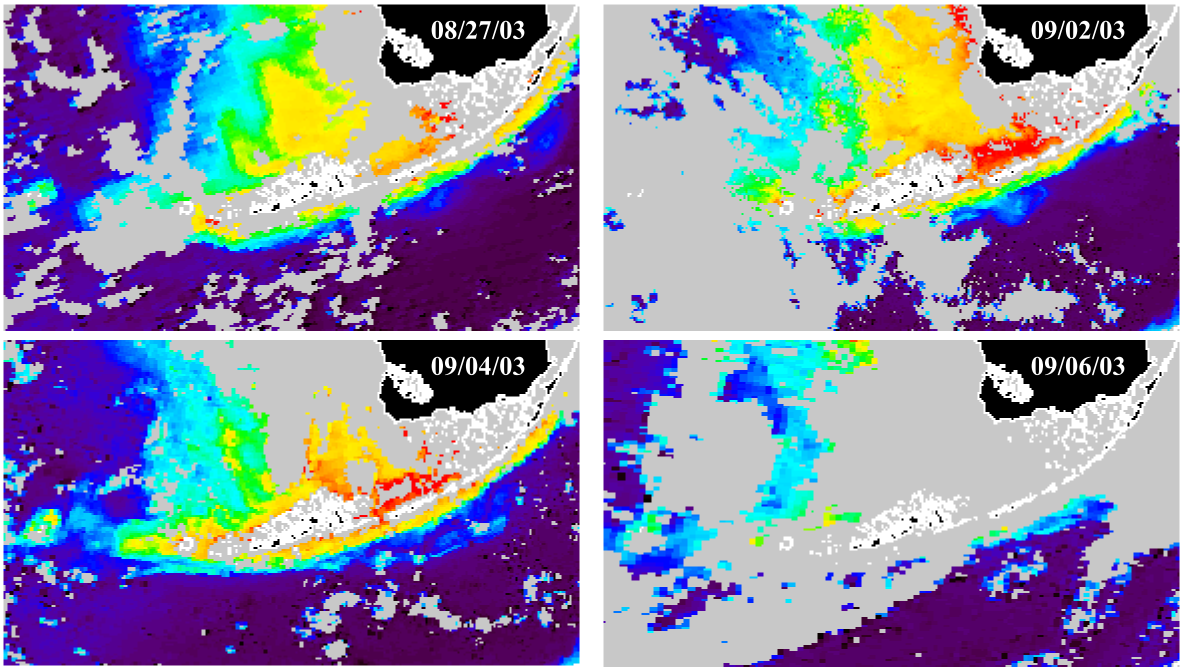

Figure 15. MODIS satellite images show color patches on the ocean side of the Florida Keys.

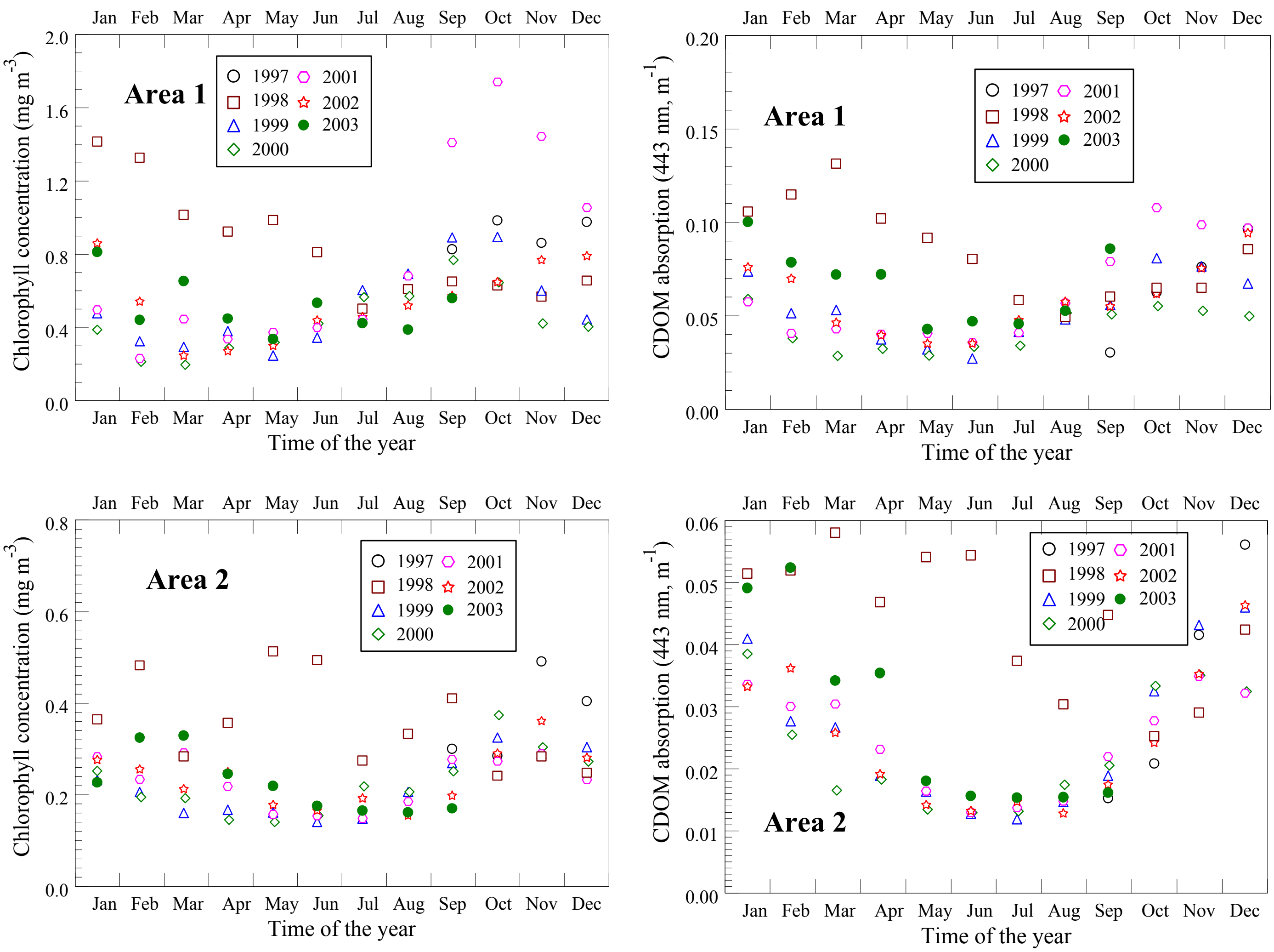

Figure 16. Monthly mean chlorophyll concentrations (in mg m^{-3}) and mean CDOM absorption coefficient (443 nm, m^{-1}) in the surface water, derived from SeaWiFS with a semi-analytical algorithm, for Area 1 and Area 2 outlined in Fig. 9. Note the differences in the y-axis scales.

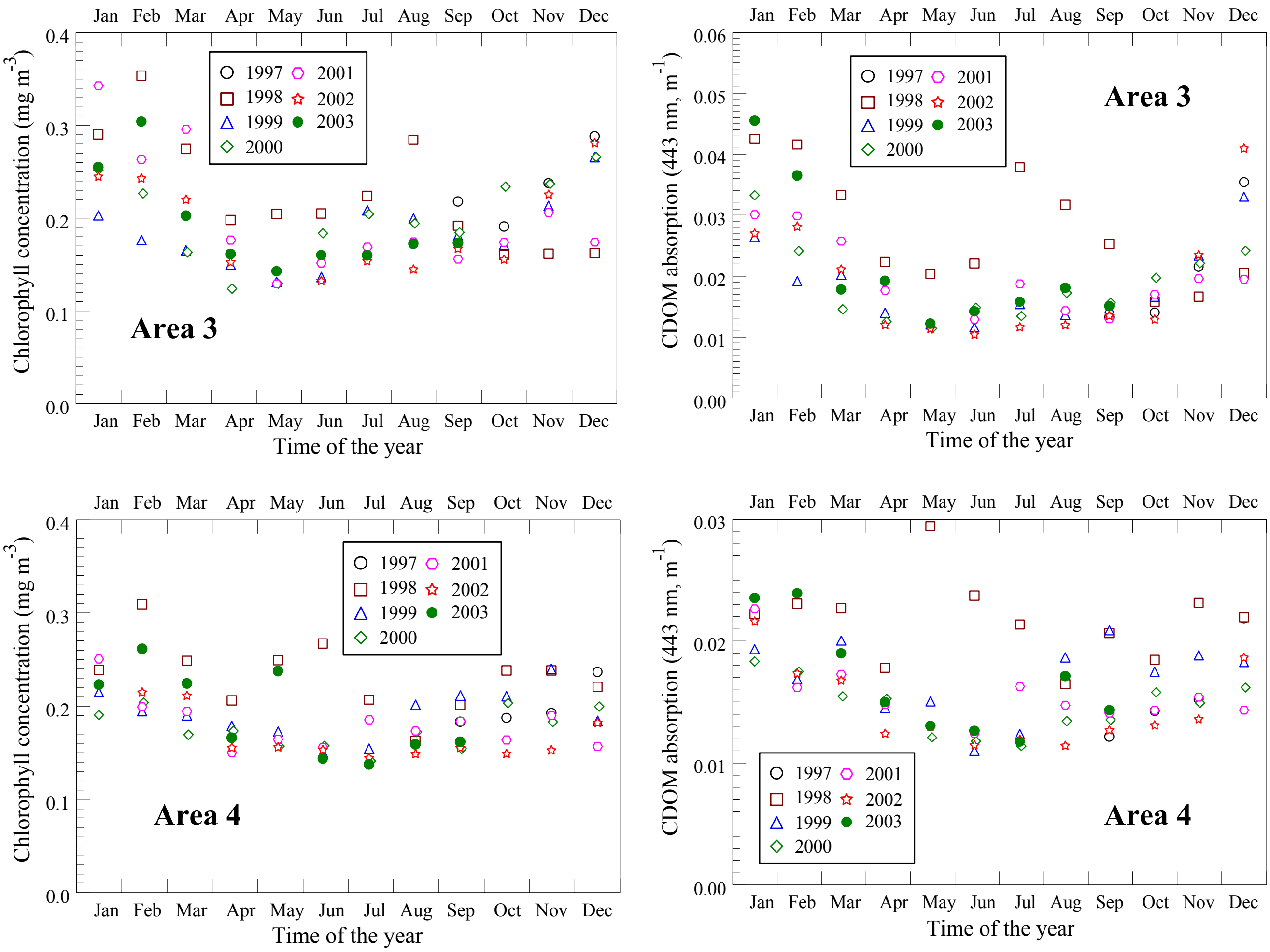

Figure 17. Monthly mean chlorophyll concentrations (in mg m^{-3}) and mean CDOM absorption coefficient (443 nm, m^{-1}) in the surface water, derived from SeaWiFS with a semi-analytical algorithm, for Area 3 and Area 4 outlined in Fig. 9. Note the differences in the y-axis scales.

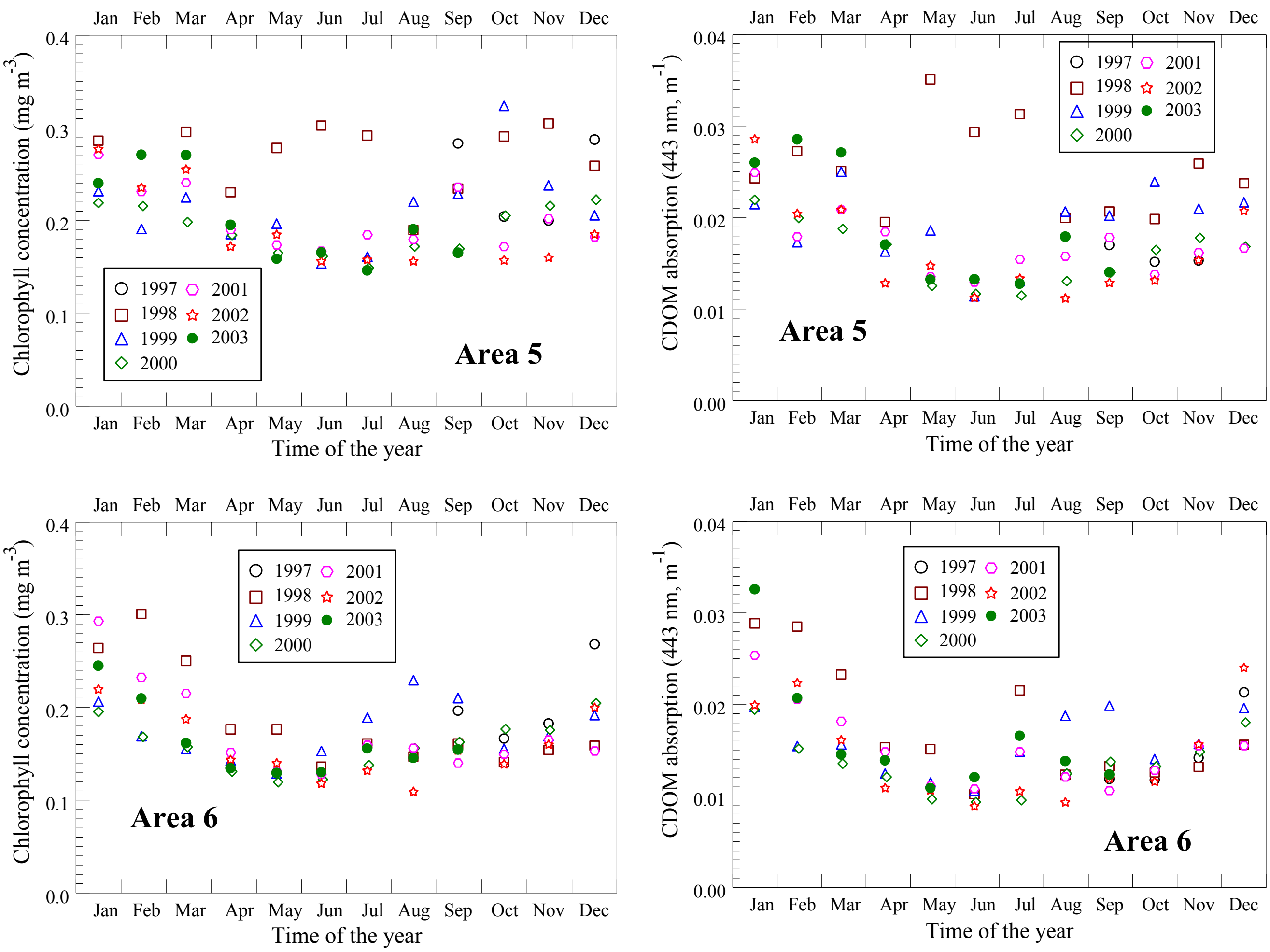

Figure 18. Monthly mean chlorophyll concentrations (in mg m^{-3}) and mean CDOM absorption coefficient (443 nm, m^{-1}) in the surface water, derived from SeaWiFS with a semi-analytical algorithm, for Area 5 and Area 6 outlined in Fig. 9.

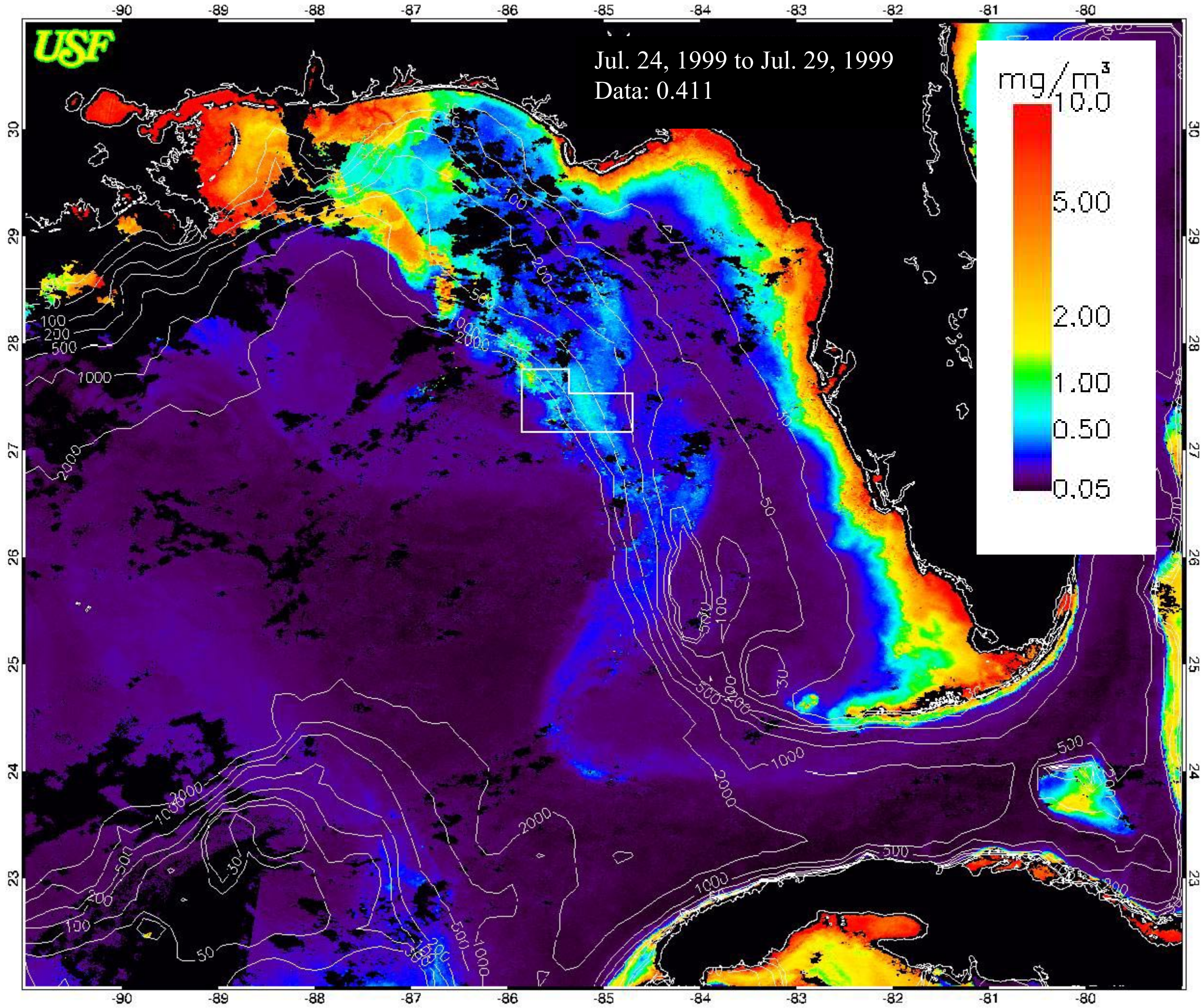

Figure 19. SeaWiFS chlorophyll composite satellite image from July 24th to July 29th, 1999. Color patterns are similar to those found in the August and September 2003 MODIS imagery, and the Mississippi water intrusion in the Florida Straits is apparent.

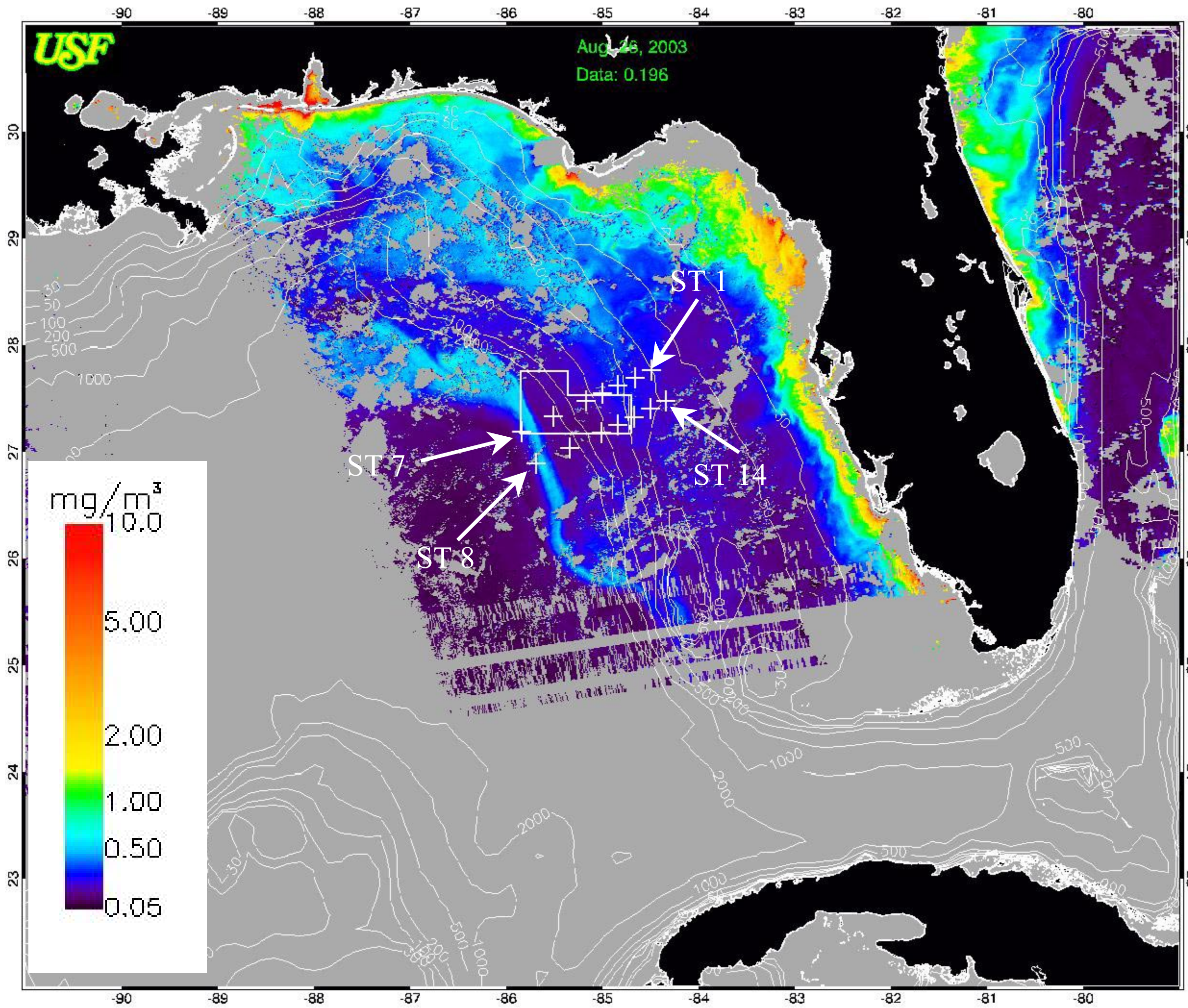

Figure 20. MODIS satellite-derived "chlorophyll" product for 26 August 2003. Overlaid on the image are the outlines (white box centered at about 27.2^{o}N 85.5^{o}W) of the dispersal area, the water depth contours (30 – 2000 m), and locations of cruise stations (from ST 1 to ST 14. Data courtesy of Ms. Danylle Spence-Ault and Dr. Gabe Vargo of USF).

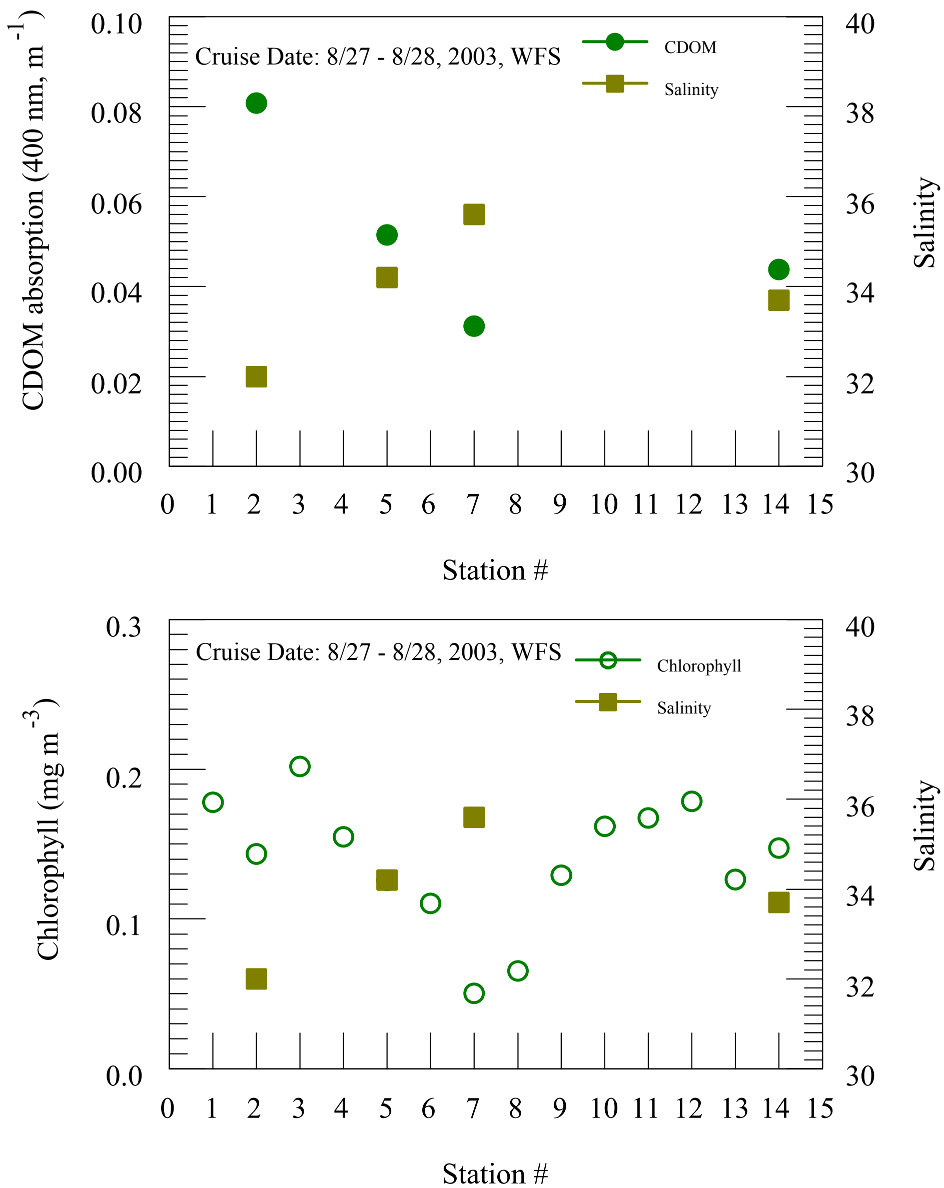

Figure 21. CDOM absorption coefficient (400 nm, m^{-1}), salinity (parts per thousand), and chlorophyll concentration (mg m^{-3}) from the surface waters of ST 1 to ST 14 (station locations shown in Fig. 19) of the 8/27 – 8/29 cruise survey (salinity and chlorophyll data courtesy of Ms. Danylle Spence-Ault and Dr. Gabe Vargo of USF).

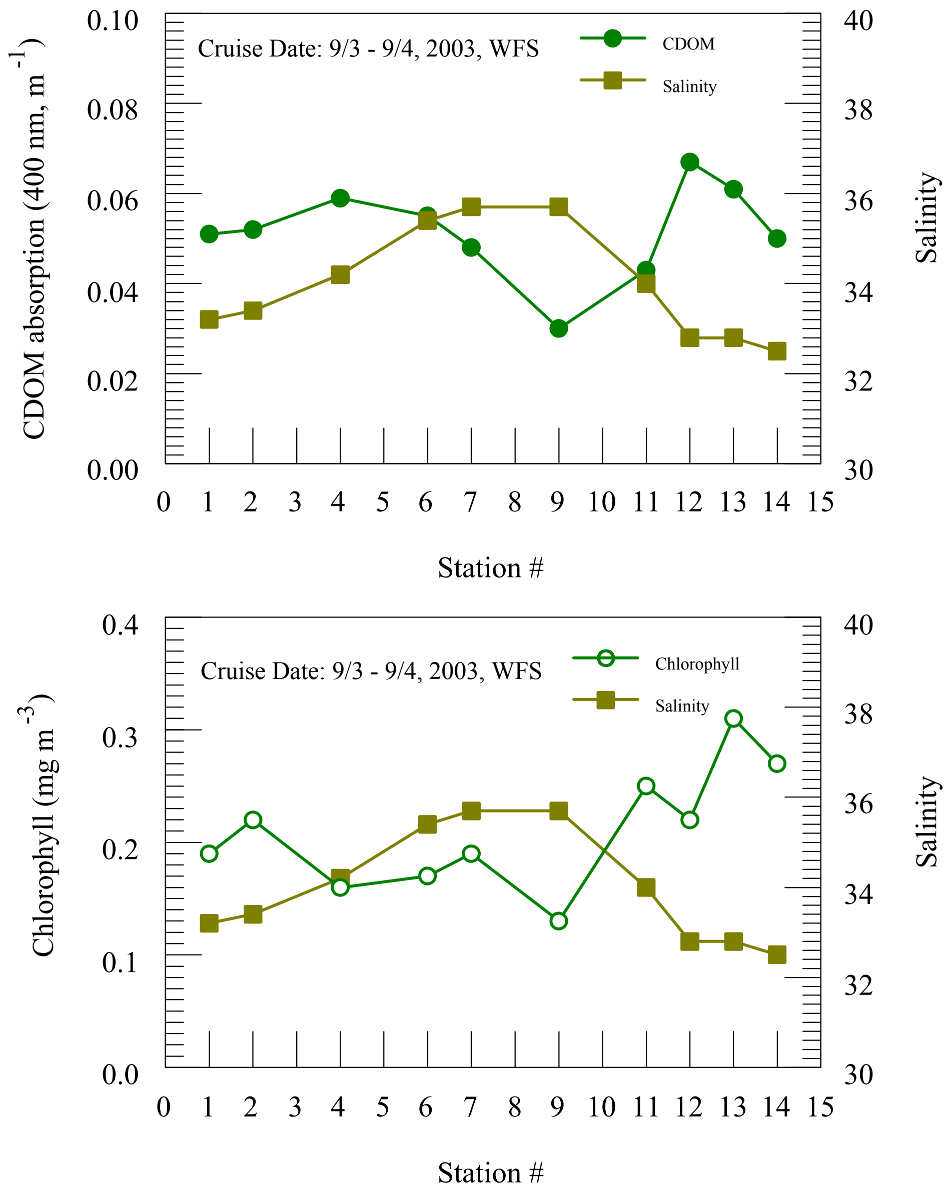

Figure 22. CDOM absorption coefficient (400 nm, m^{-1}), salinity (parts per thousand), and chlorophyll concentration (mg m^{-3}) from the surface waters of ST 1 to ST 14 (station locations shown in Fig. 19) of the 9/3 – 9/4 cruise survey (salinity and chlorophyll data courtesy of Ms. Danylle Spence-Ault and Dr. Gabe Vargo of USF).

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Appendix A. Satellite instruments and image interpretation

Satellite Instruments

The satellite instruments used in this monitoring project include the Sea-viewing Wide Field-of-View Sensor (SeaWiFS, http://seawifs.gsfc.nasa.gov), the Moderate Resolution Imaging Spectroradiometer (MODIS, http://modis.marine.usf.edu), and the Advanced Very High Resolution Radiometer (AVHRR, http://www.ngdc.noaa.gov/seg/globsys/avhrr.shtml). Table 1 lists the characteristics of these instruments.

Table 1. Satellite instruments used in the monitoring project.

Satellite	*Instrument*	*Owner*	*Measure*	*Swath (km)*	*Resolution (km)*	*Availability*
SeaStar	SeaWiFS	Orbimage	color	> 2000	~1.1	daily
Terra	MODIS	NASA	color temperature	> 2000	~1.1	daily
Aqua	MODIS	NASA	color temperature	> 2000	~1.1	daily
POES	AVHRR	NOAA	temperature	> 2000	~1.1	daily

These satellites instruments survey the surface ocean every day at approximately the same local time. They provide a synoptic view of the surface ocean (color and temperature) at regional to global scales. The satellite data are captured, processed, and archived by the Institute for Marine Remote Sensing (IMaRS, http://imars.usf.edu) at the College of Marine Science, University of South Florida. The algorithms used to generate these imagery data products can be found under IMaRS website http://imars.usf.edu.

Sea surface height data are obtained from the Colorado Center for Astrodynamics Research (CCAR) at the University of Colorado, Boulder (Dr. Robert Leben; http://www-ccar.colorado.edu/~realtime/gsfc_gom-real-time_ssh/)

Online Images for Piney Point

Near real-time imagery can be found at http://imars.usf.edu/Piney_Point for public access and distribution. Note, however, while MODIS and AVHRR data are public domain, SeaWiFS data is property of Orbimage, Inc. (http://www.orbimage.com). Please contact Orbimage for any non-NASA SeaWiFS program use of data or derived imagery. Reproduction or redistribution (including media) of SeaWiFS data/imagery is prohibited without the permission or license from Orbimage.

Conventions used to name a file (image) at http://imars.usf.edu/Piney_Point are as follows:

SeaWiFS: SYYYYDDDHHMM: YYYY for year, DDD for day of the year, HH for GMT (Greenwich Mean Time) hour, MM for minutes. The images show surface chlorophyll concentrations of the ocean, as derived by the standard NASA algorithms (SeaDAS version 4.4).

MODIS: MODIS.YYYYDDD.HHMM: similar to SeaWiFS. There are several data types available for MODIS, resulted from standard NASA algorithms for MODIS, including: surface chlorophyll concentrations, surface colored dissolved organic matter (CDOM, also called Gelbstoff) abundance, surface temperature, and red-green-blue (RGB) composite images.

AVHRR: nNN.YYYYDDD.HHm: NN for NOAA satellite number, MM for month, DD for day, HH for GMT hour, mm for minutes. The images show sea surface temperature.

Color interpretation of satellite images

It is important to note that by no means do the colors shown on the images reflect the actual color of the ocean. Instead, they simply represent various relative concentrations of water constituents. The color-concentration relationship can be found on a color legend, but please note caveats provided below. RGB composite imagery to some extent do reflect the real color of the ocean.

Various constituents in both particulate and dissolved forms determine ocean color. In the open Gulf the color is generally dominated by phytoplankton, the living, tiny organisms which serve as the base of the food chain. In waters where coastal runoff (river discharge and other terrestrial runoff) is significant the color is a mixture of phytoplankton, dissolved matter, and suspended inorganic particles (clay, sediments, etc.) where any of these species can dominate the color.

The chlorophyll images (with "florida" in the SeaWiFS filenames and with "chlor" in the MODIS filenames) show the surface concentration (in milligrams per cubic meter) of phytoplankton pigment, chlorophyll-*a* (the photosynthetic pigment that also exists in all green tree leaves). High values are indications of biologically active waters. The values are more accurate for open Gulf waters without river intrusion than for coastal waters or river plume waters. Indeed the yellow-red colors seen off the coasts reflect not only chlorophyll but also dissolved matter and suspended sediments (i.e., they are often overestimates of the real chlorophyll concentrations). The river plume band seen offshore in the Gulf of Mexico may contain high concentrations of colored dissolved organic matter, as well as variable amounts of plankton.

The temperature images show the surface temperature of the ocean. Different temperatures are represented by different colors (see color legend). Waters of various origins sometimes display different colors. For example waters from the tropics often show higher temperatures than the Gulf water.

IMaRS Disclaimer

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